THE EVALUATION OF SOFTWARE FOR WIND TURBINE SITING IN SIMPLE AND COMPLEX TERRAIN

A thesis
submitted in fulfilment
of the requirements for the Degree
of
Master of Engineering
in the
University of Canterbury

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1999

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IV. APPLICATION TO COMPLEX TERRAIN

To my dearest beloved Mother and Father

ACKNOWLEDGMENTS

My biggest debt of gratitude is owed to my wonderful supervisor, Tony Bowen, for his efficiency, encouragement, patience and invaluable knowledge, who helped me through out my masters program with unconditional advise and guidance. Also to all staff of the Mechanical Engineering for their help and support.

Mention must be made of all those staff in Geography Department who helped me to obtain the contour maps; also, staff in the Civil Engineering Department for allowing and assisting me to use their map digitising equipment.

I wish to place on record my appreciation of people in Risϕ National Laboratory of Denmark who helped me with my inquires in using the WAsP Program. Also, many thanks to Mr. Wayne O'Hara for helping me with the proof reading.

Finally, sincere thanks and recognition is due to my wife, Helen, for her consistent support and encouragement through my course of study.

SUMMARY

Over the past two decades, methods and numerical techniques for the assessment of the wind energy resource over simple and complex terrain have developed considerably. The European regional study represents the most detailed of such efforts. As a part of this study, the Wind Atlas Analysis and Application Program (WAsP) was developed. WAsP is a PC based program and was developed for the purpose of wind climate estimation with special regard to wind energy applications. WAsP is now increasingly used worldwide in wind turbine site assessments.

A brief description of WAsP is given and then it is applied to predict wind speed-ups over a smooth isolated hill. Its predictions compare well with the field data on the upwind side of the hill. But, at the lee side WAsP tends to over-estimate wind speeds.

The program is also employed to predict average mean-wind speeds for all directions for a number of sites in steep hilly terrain - the Port Hills of Christchurch. The results are compared to a unique set of field measurements and WAsP capabilities are investigated. WAsP predictions are reliable for sites with gentle slopes (less than 0.3 gradient) and smooth peaks. However, WAsP predictions for sites with more rugged slopes are 10% to 25% larger than measured field values.

WAsP accuracy in predicting wind speeds (and hence wind energy distribution) is highly dependent on the accuracy of map data, the ruggedness at the site, and the level of atmospheric correlation between the reference and predicted sites. The sign and magnitude of the prediction error due to site ruggedness is proportional to the difference in ruggedness between the predicted and the reference site. In order to quantify this error, a utility program (RIX) WAsP applied to the results from the Port Hills. The RIX program produces satisfactory results for the Port Hills, particularly, for more rugged sites where WAsP errors are maximum, e.g. Sugar Loaf. The RIX program can be used to determine the degree of ruggedness around a site. In this way, a wind engineer is able to use this quantified ruggedness, for a prevailing wind direction, to adjust wind energy predictions produced by WAsP.

CHAPTER I

INTRODUCTION

HAPPY WIND
Oh, happy wind, how sweet
Thy life must be!
The great, proud fields of gold
Run after thee!
And here are flowers, with heads
To nod and shake;
And dreaming butterflies
To tease and wake.
Oh, happy wind, I say,
To be alive this day.
W.H. Davies

1.1 MAN AND WIND, AN INEXHAUSTIBLE PARTNERSHIP

Wind and its majestic power have captured man's fascination throughout history. Wind has always been a powerful appliance for poets, philosophers, engineers and whosoever has tried to acknowledge and appreciate the exalted qualities of our mother planet, the Earth. Wind is one of few earthly amenities that not only have engineers tried for a myriad of years to harvest its resources, but poets have also lavishly enjoyed and employed in their poems.

1.2 HISTORY OF WIND TURBINE TECHNOLOGY

The first wind turbines were probably simple vertical axis devices, such as those used in Persia as early as about 200 BC for grinding grain. Such primitive types of windmills are still found in use in many Middle Eastern and Mediterranean regions such as Persia (Iran) and Spain. The use of these vertical axis mills subsequently spread throughout the Islamic world. Later, horizontal axis windmills, consisting of up to ten wooden booms, rigged with jib sails were developed.

By the eleventh century AD, windmills were in extensive use in the Middle East and were introduced to Europe in the thirteenth century by returning Crusaders. By the 14th century the Dutch had taken the lead in improving the design of windmills and used them extensively thereafter. By the middle of the 19th century, some 9,000 windmills were being used in the Netherlands for a wide variety of purposes [1].

With the introduction of steam engines, during the Industrial Revolution, the use of wind power in Holland and other places started to decline. The Dutch introduced many improvements in the design of windmills. More modern designs substituted sheet metal for the cloth sails and aerodynamic principles were increasingly corporated in rotor designs.

Since the mid-nineteenth century, wind turbine technology has taken a quantum leap. During World War II, the Danes developed and operated a number of new types of large-scale wind machines for producing electricity. American engineers also took an active role in designing large-scale wind turbines. Smith-Putnam 1.25MW unit is the classic example which was the largest wind turbine prior to the late 1970's. It operated intermittently from 1941 t0 1945 when it was shut down after a blade failure. Since then, increasing crude oil prices, environmental pressures and augmenting interests (including political) in renewable sources of energy created a demand for efficient and more cost effective designs in wind turbine technology. Consequently, innovative designs coupled with the latest state of the art rotor designs have brought forward machines such as 500kW German Enercon turbines. Parallel to these advancements, significant developments have been made in predicting techniques for wind turbine site evaluation assessments. These are discussed in the next section.

1.3 WIND TURBINE SITE EVALUATION

Irrespective of the nature of demand, all wind turbine developments first require an acceptable site evaluation. The major and foremost part of this process is an estimation of wind resource. Next, the site's accessibility to heavy machinery, the availability of essential civil engineering technology and closeness to the power network is studied. Rationally, the most cost effective assessment is used in actual development.

In some respects, the physical site is already determined by other factors so that no great competitive advantage can be made, except improvements in wind resource assessment. Determination of site access may be self evident and not open to improvement. The determination of the availability of essential site construction technology is also circumstantial. Ingham[2] argues that at any one time the marginal utility of commutative advantage is small. However, large savings can be made in optimising the resource potential of a site by utilising better techniques in predicting wind speed and hence wind energy flux for that site. Accurate assessment of output is critical for a reliable financial plan and could mean the difference between success and financial ruin for the developer. Ingham [2] considers a possible improvement of up to 20% above the initial wind resource assessment. The physical basis for site interpolations is crucial to such assessments. Ingham [2] has based his site optimisations on the dedicated wind resource assessment model, the Wind Application program (WAsP) which is the subject of study and evaluation in this research.

1.4 METHODS OF RESOURCE ASSESSMENT

More and more attention is being made to the study of wind flow behaviour over complex terrain as the fossil fuel resources are dwindling and their emission gases are causing increasing concern over the greenhouse effect. Fossil fuel generated electricity supply contributes an estimated 30% to the total anthropogenic emission of gases that warm the atmosphere. The publication of 'Our Common Future' in 1987 by the World Commission on Environment and Development (WCED) and the Rio Earth Summit, by heads of government, have established an international protocol on the reduction of greenhouse gas emissions (WECD 1988). The surge in interest in WECS due to greenhouse related policies has renewed high levels of demand on the development of more reliable techniques in estimating wind energy statistics over hilly terrain. As economic interests in wind energy have grown, regional studies have also become more elaborate, integrating more resource information, as in the Wind Atlas of Europe, Troen and Petersen [3].

1.5 STUDY OF WIND FLOW OVER COMPLEX TERRAIN

The study of wind flow over complex terrain is a rich area of research involving an impressive range of flow phenomena. This category has many applications in wind engineering such as building exposure, pollution dispersal, forestry and horticultural, transport and most importantly, in wind turbine siting.

There are now a vast amounts of field data available for low isolated hills backed by wind tunnel measurements and some successful numerical prediction models. For example, the international investigation of Askervein Hill led by the Canadian Atmospheric Environment Service (Toronto), produced a large amount of full scale and model data which were used to develop numerical models and to compile building codes.

Prediction techniques and computer models are becoming available for the estimation of wind speeds over simple and complex terrain. However, a great deal of effort and research is still needed to refine these prediction techniques. This is more the case with understanding and predicting the behaviour of mean wind speeds and turbulence in complex terrain and real situations. Most important are the effects of separation in the lee side of the terrain. As a result of this research work, numerical models such as BZ model (utilised in Wind Atlas and Application Program - WAsP Orographic model), NOABL models, NUATMOS and MS3DJH/3R model have been compiled. Each model has its own limitations and the accuracy and reliability of all have been questioned for non-attached flows.

1.5.1 Scientific and simple technical basis behind flow models

Although there had earlier been a number of measurements of wind speeds on hill tops (Davidson et. al, [7]) and some theories concerning the speed-up caused by terrain features (Golding [8], Ch. 7), a detailed and quantitative theory of boundary layer flow over low hills has only been established in the last two decades or so. Developments are still in progress on some aspects of the theory but the key document is probably the paper by Jackson and Hunt [6]. Working in terms of 'fractional speed-up ratios' they showed:

$$\Delta S = \frac{U(\Delta Z) - U_0(\Delta Z)}{U_0(\Delta Z)}$$

where ΔZ is the height above the local terrain and $U_0(\Delta Z)$ is the 'undisturbed' upstream velocity profile. They developed a theory to predict ΔS (speed-up) within a near-surface or 'inner' layer for flow over low two dimensional hills. Mason and Skeys [13] extended the theory to three-dimensional hills, while Walmsley et al. [11] and Taylor et al. [12] discussed further extensions to the theory and applications to real terrain.

Hunt [10] has reviewed simple rules-of-thumb for estimating maximum, near surface, values of ΔS above hill and ridge tops. He suggested that for 2D ridges:

$$\Delta S \approx 2\frac{h}{L}$$

where h is the hill height and L is defined as 'the distance from the hilltop to the upstream point where the elevation is half its maximum. For a 3-D axially symmetric hill, Hunt implies that the 2-D result will apply but Taylor and Lee [5] suggest that:

$$\Delta S \approx 1.6\frac{h}{L}$$

is a better estimate. For a typical low hill such as Askervein Hill with h = 116m and L~250m, it is thus found that the near-surface wind speed is increased by 70% to 80%. For slightly steeper hills, increases of up to 100% to 130% are not uncommon. These results are later compared with WAsP predictions.

Since the theoretical kinetic energy and hence the power available to a WECS is proportional to the cube of the wind speed, these increases are of enormous significance in the selection of suitable sites for wind turbines. For example, a 5% height increase can have 5% impact on the mean wind speed - possibly at hub height - resulting in a 15% increase of the available power. In addition to modifications to the mean flow, the straining of the flow during its passage over a hill will modify the turbulence structure. There are some theories concerning this phenomenon (see, for example, Hunt [10]) but there is still relatively little known about turbulence structure in the flow over hills. There will be of considerable significance to the design of large WECS or other structures to be erected on hill top sites.

These fundamental works have paved the way for computational codes to be written such as the BZ, NAOBL, MS3DJH/3R, and NUATMOS models.

1.6 SIGNIFICANCE OF THIS STUDY

Amongst above models, the BZ model which is a part of the WAsP program, has been used more extensively for wind turbine site assessments by wind engineers. Both the MS3DJH/3R and NOABL models which are not easy to use, require substantial post-processing and are slower by a factor of 100 than the BZ model, Barnard [4]. BZ model can be run on portable computers. The WAsP program has been used to position wind turbines on Altamont Pass in the USA, the site of the world's largest wind turbine installation. It has also been used extensively in Europe and Australasia.

Wind Power is becoming the fastest growing renewable energy and it has been successfully implemented in many countries such as the USA, The Philippines, India, Indonesia, China, Germany, Greece, Britain, Denmark, and New Zealand. In majority of these developments, wind farms have been sited in hilly terrain. The accurate prediction of wind energy statistics has been paramount to the success of these projects. In New Zealand, because of the relatively cheap electricity prices and fewer environmental problems, application of WECS has been relatively slow. However, the first wind farm in New Zealand has been running for over three years with significant world class achievements. The WAsP program has already been used by the Wind Power Group of Designpower in wind turbine site assessments.

Since the WAsP package is now increasingly used worldwide in site assessments, it is vitally important to establish both the accuracy and the inadequacies of this package in predicting wind speeds and wind energy statistics over complex terrain. It is not uncommon for the majority of candidate sites for wind power generation to be in hilly terrain. This is the case for almost all sites considered for wind energy generation in New Zealand. Long term involvement of the University of Canterbury School of Engineering in wind research provides an ideal opportunity to calibrate and determine the performance envelope of this package in dealing with a smooth isolated hill (e.g. Askervein Hill), and more importantly over complex terrain (e.g. Port Hills of Christchurch). Conclusions made by this study are aimed at establishing confidence in the ability of the WAsP program to estimate wind energy statistics over hilly terrain. This study aims to show how the program should be used to give best practical results and endeavours to shed more light on its potential.

1.6.1 ORGANISATION OF THIS REPORT

The main objective of this study is an evaluation of the WAsP program in predicting mean wind speed over complex terrain. Chapter 2 gives a brief description of the WAsP program and its basic analytical elements. It discusses the format of input data required to execute a successful WAsP session. Chapter 3 discusses WAsP application to a simple and smooth isolated hill to calculate wind speed-up values at several sites over the hill; and compares them with the actual measured field data. Chapter 4 investigates WAsP's ability to extrapolate wind data from a reference site on a flat terrain to several sites on a near-by hilly terrain. WAsP predictions are compared with the recorded field data and its limitations are studied. Full discussions of results with other relevant analysis are presented in this section. Chapter 5 looks at a utility program designed in an attempt to better understand WAsP predictions in hilly terrain. Chapter 6 presents a very brief description of other numerical packages currently applied to complex terrain flow calculations. Their ability of estimating the mean wind speeds over a simple hill and a mountainous terrain is compared. This report finishes with a number of conclusions.

CHAPTER II

WIND ATLAS ANALYSIS AND APPLICATION PROGRAM (WAsP)

2.1 INTRODUCTION

Over the past two decades, methods and numerical techniques for the assessment of wind energy resource over complex terrain have developed considerably. Jackson and Hunt [16] provided the only basic analytical theory for the mean flow over low, smooth hills of low curvature which later was well established and developed further by Jackson [14,15], Mason and Skeys [13] and others. These fundamental works paved the way for advanced techniques to be evolved from statistical methods with data interpolation, such as used by Troen and Petersen [3]. This reflects an improved understanding of boundary layer flow over complex terrain and is widely reviewed, Taylor et al [16] and Finnigan [17]. As economic and environmental interest in wind energy has grown, regional studies have also become broader and more elaborate, integrating more resource information, as in the Wind Atlas of Europe (Petersen et al [18], Troen and Peterson [3]).

The European regional study represents the most elaborate of such efforts. As a part of this study, the Wind Atlas Analysis and Application Program (WAsP) was developed. WAsP is a commercially PC based program for 3 dimensional exploration of wind data. The program was developed for the purpose of wind climate estimation with special regard to wind energy applications. It is based on existing numerical models for wind flow and uses statistical data interpolation methods to cope with the prediction of wind energy statistics for specific sites. It applies the Wind Atlas Method in taking into account the effects of different roughness conditions, sheltering effects due to nearby buildings and other obstacles, and the modification of the wind speed imposed by complex terrain.

WAsP converts the recorded wind data into a wind atlas data set. In a wind atlas data set the wind observations have been "cleaned" with respect to site specific conditions and reduced to standard conditions. Using a wind atlas data set calculated by WAsP, the program could estimate the wind climate at a particular point by performing the inverse calculation as is used to generate a wind atlas. WAsP then calculates the total energy content of the mean wind (wind resource). Furthermore, an estimate of the actual yearly mean power production of a wind turbine can be obtained by providing WAsP with the power curve of the turbine in question. The wind turbine output can be calculated for specified sites or may be mapped for an entire area of a wind farm. Similarly, the wind resource may be mapped on a grid of specified sites.

2.2 THE WIND ATLAS METHOD

The wind Atlas Method provides a framework of extrapolation of wind data from one site to another. The principles of the method are outlined in the Danish Wind Atlas (Petersen et al [19]) and further developed in the European Wind Atlas (Troen and Petersen [3]).

The method requires that the two sites in question are subject to the same overall weather systems. WAsP generates a wind atlas data set in 5 major steps:

1. The setting up of terrain models for the observational site (reference site) and the site/sites of interest.
2. Vertical extrapolation procedure linking the wind observations to free wind conditions not influenced by the frictional forces of the atmospheric boundary layer.
3. Horizontal extrapolation of the wind observations performed at the reference site above the planetary boundary layer.
4. A reverse vertical extrapolation procedure linking the free wind data to the specific conditions at the site of interest ("downward transformation").
5. Analysis of these data in terms of the Weibull distribution function. The two Weibull parameters obtained constitute the wind atlas for the region in question and is the starting point for wind energy siting calculations.

Wind atlas data are truly processed data in the sense that the wind atlas statistics at a given station have been "cleaned" to certain standard conditions. As such, they are the natural meteorological basis for a wind turbine siting project (Mortensen et al [21]).

2.3 DESCRIPTION OF SOFTWARE

The basic analytical elements of the WAsP program are described as:

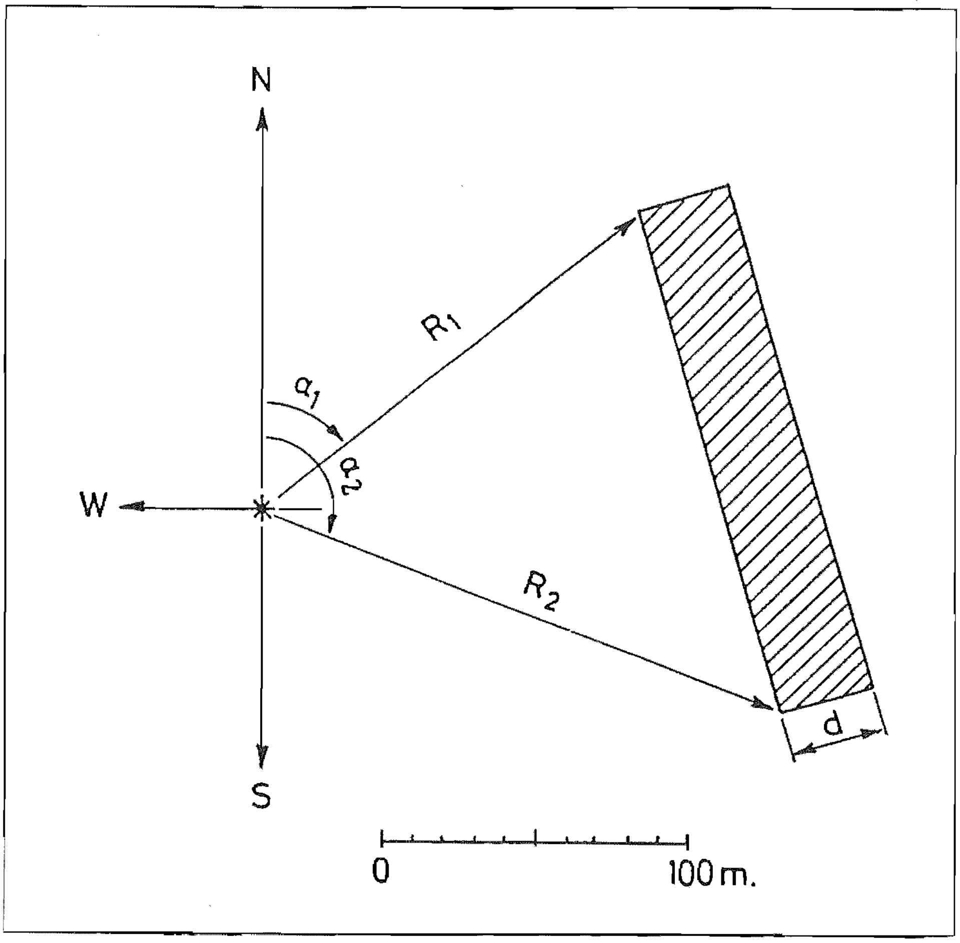
2.3.1 The shelter model

The model is based on a paper by Perera [20], which describes shelter behind 2-dimensional solid and porous fences. WAsP provides facilities for shelter calculation behind three-dimensional obstacles taking into account lateral mixing at the edges, and the possible interference of other nearby obstacles.

Obstacles are considered by WAsP as 'boxes' with a rectangular cross-section. Each obstacle must be assigned by the position relative to the site, its dimensions and must be assigned a porosity. In practical situations the problem arises when determining a terrain feature whether should be regarded as a roughness element or as an obstacle. WAsP provides this guideline:

- If the point of interest (anemometer or wind turbine hub) is closer than about 50 obstacle heights to the obstacle and closer than about three obstacle heights to the ground, the object should probably be regarded as an obstacle.
- If the point of interest is further away from the above conditions, the object should most likely be included in the roughness description.

WAsP can handle up to 50 obstacles at a time. One limitation of the model is that very close to an obstacle, the obstacle model will not yield realistic results where it tends to overestimate the wind speed by sometimes a factor of two. Obstacles are not directly linked to the topographic map. Figure 2.1 shows the position of an obstacle with its positional parameters relative to a specific site.



	Position of site
α_1	angle from N to first corner (deg)
R_1	radial distance to first corner (m)
α_2	angle from N to second corner (deg)
R_2	radial distance to second corner (m)
h	height of obstacle (m)
d	depth of obstacle (m)
P	estimated porosity (m)

Figure 2.1. Relative position of an obstacle to a specific site (Mortensen et al [21]).

2.3.2 The roughness change model

The model takes into account the influences of changes in the roughness of the near site terrain (up to 10000m) and uses a sub-program to model the wind flow downstream in the growing internal boundary layer. The roughness classification applied in the WAsP program is made with 8 azimuth sector divisions for the site of interest and each sector can handle 10 consecutive changes of surface roughness.

WAsP describes the roughness characteristics of the terrain surrounding a site in two ways:

- in the form of a site specific roughness description - a roughness rose. In this case the roughness condition at one site are described sector by sector as seen from the site. The description contains the distance to and magnitude of the roughness changes that occur in each sector.

- Or, in the form of a digitised map of roughness-change lines, i.e. lines separating areas of equal roughness (length). Roughness-change lines are assigned two values: the roughness lengths Z_{01} and Z_{02} found on either side of the line with specified starting and end points.

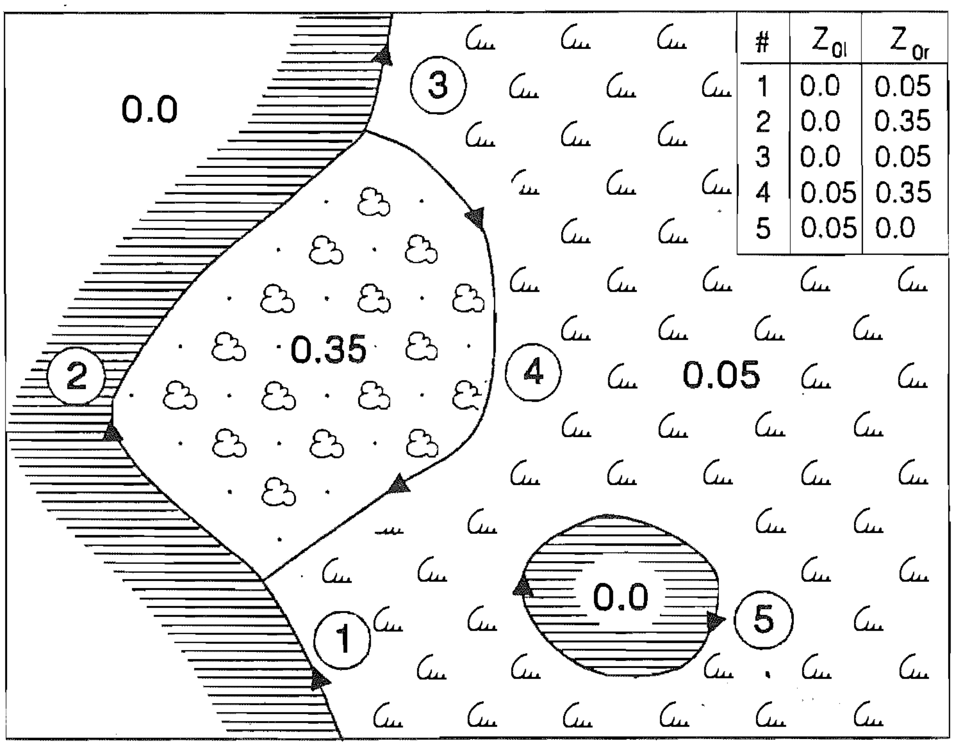


Figure 2.2. Examples of roughness-change lines. Water surfaces must be assigned a roughness length of zero meters (Mortensen et al [21])

2.3.3 The Orographic model

WAsP utilises the BZ model (Troen and Baas [22]) to calculate the wind speed perturbations induced by orographic features. The model is based on the linearisation of the equation of motion and the use of Fourier transforms and independent calculation of velocity perturbation for each wave number vector. It utilises a spectral method modeled on the work of Jackson and Hunt [16]. This decomposition allows for the treatment of the wind flow over real 3D terrain provided that the horizontal dimensions are less than 1-2 km and the slopes are not so steep as to cause flow separation (no greater than 30%). The model employs a "zooming" polar grid with resolution concentrated at the single point of greatest interest. The input to the model are height contours and the model examines all the grid points when estimating the wind conditions at a site. The scale of the grid is adjusted depending on the size of the domain described in the contour lines. With an outer radius of 50 km, the resolution at the center is 10m.

The BZ model integrates the roughness conditions of the terrain surface into the spectral or scale decomposition. The "inner-layer" structure is calculated using a balance condition between surface stress, advection and the pressure gradient (Morgensen et al [21]). It uses an atmospheric boundary layer thickness of ~ 1 km to force the large scale (more than a few kilometers) flow around high-altitude areas.

The input data to the WAsP orographic model is in the form a digitised map stored in a map file. This file may contain height contours only, roughness-change lines only, or both. The WAsP map file consists of strings of coordinate pairs, each string specifying one height contour line or one roughness-change line. The coordinates may be given as (x,y) - values in a Cartesian coordinate system or as (r, θ) - values in a polar system for each height category. With the standard version of WAsP, the map file must not contain more than approximately 10,000 points. The bigger version of WAsP - *BIGWASP* can handle files of up to 16,000 data points.

2.4 METEOROLOGICAL INPUT DATA TO WAsP

The meteorological input to WAsP could be:
raw data: which are measurements of wind speed and direction either in the form of time-series or compiled into a meteorological table. These data reflect the specific conditions at the exact position of measurement. However they need to be extrapolated and one must take into account, the nearby obstacles, the surface roughness conditions and the effect of terrain height variations around the meteorological station. Only after "cleaning" the data in this way can they be used for estimating the wind climate at other places around the meteorological station.

processed data: WAsP is capable of reading and transforming time-series data in any format into a table that gives the frequency of occurrence of wind speed versus wind direction. This histogram table is used later by WAsP in the analysis of the wind climate. When scanning the raw data, WAsP gives the user the following options:

- specifying how raw data may be scanned, for example, to scan only every second or third record;
- setting the lower and upper limits for wind speed and direction;
- offering the possibility of scaling the data linearly if the wind measurements are not given in [m/s] and [deg], or the data need recalibration. An offset factor can also be specified both for wind speed and direction;
- data discretisation. If raw data has already been processed and truncated (which is usually practiced by some meteorological stations), it causes error with the default setting for the wind speed bins of 1 m/s. This is because the wind speed value $u= n$ (n is an integer) will add to the nth bin which is subsequently represented by its midpoint $u_m= n + 1/2$. WAsP specifies a discretisation factor to avoid this shifting of wind speed distribution (Mortensen et al [21]).

While processing the data, WAsP displays the time traces of wind speed and direction on the graphic screen. It also provides the user with a scatter plot of wind observations as points in a polar coordinate system. The final processed data is displayed in the form of a meteorological table.

2.5 DISPLAY OF RESULTS IN WAsP

2.5.1 The status display

If all the facilities of WAsP are executed, this display provides an overview of the current status of the program. Figure 2.3 shows a typical WAsP status display.

Each entry (box) in the display lists a file name if an input file has been entered (e.g. A:\ASKERVEI\ATLAS\ASKERVEI.LIB). An identifying text string, usually the first line of the file, is shown in the right-hand side of the box or below the file name (DATA and WECS). Apart from the OROGRAPHY entry, the file name and text of any saved file is also shown. The OROGRAPHY entry states the coordinates (x,y) of the current site and - to the right - the height above sea level of the site, the radial grid size at the center of the model and the model radius, respectively. These members are all given in meters. In the lower right-hand corner of the display the current drive and path are shown (in this case C:\WASP) and also the name of the saved file, if one has been opened (C:\WAsP..). The main menu is shown below the status display. Two lines list the key-words for entering the sub-menus and - when employed from left to right - also leads the user through WAsP session.

```
+ATLAS-----------------------------------------------------------------------+
|____________________________________:Askervien Hill Wind Data, 1982-1983   |
|A:\ASKERVEI\ATLAS\ASKERVEI.LIB_______:Askervien Hill Wind Data, 1982-1983   |
+----------------------------------------------------------------------------+

+OROGRAPHY-------------------------------------------------------------------+
|C:\ASKERVEI\MAPS\ASKI.MAP:+ CONTOUR MAP OF ASKERVEIN HILL                   |
|(    75387,     23735),       123)       : dr,   R  :     1.0      2825.    |
+ROUGHNESS-------------------------------------------------------------------|
|____________________________________:Roughness Length = 3 cm.               |
|____________________________________:_______________________________________|
+OBSTACLE--------------------------------------------------------------------|
|____________________________________:_______________________________________|
|____________________________________:_______________________________________|
+----------------------------------------------------------------------------+

+TABLE-(48 m a.g.l.)------------------++WECS---------------------------------+
|C:\ASKERVEI\WIND\ASKERVEI.TAB        ||_____________________________________|
|Askervien Hill Wind Data, 1982-1983  ||_____________________________________|
|_____________________________________|+-------------------------------------+
|_____________________________________| _ C:\WASP40\
+-------------------------------------+ _ C:\ASKERVEI\DUMP\ASKIHT.DMP
  DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS WECS HEIGHT
  DISPLAY RESOURCEFILE FREQUENCY DOS HELP RETURN STOP
WAsP>
```

Figure 2.3. The status display of WAsP.

2.5.2 The result display

This display shows the estimated wind climate in tabular form, calculated employing the current wind atlas data set and the site description, see Figure 2.4. The calculations supply information on the overall mean wind speed (M), the total energy content of the wind (E), the mean power which is expected to be generated by the turbine (P), and the Weibull distribution parameters (A and k)[1]. Furthermore, for each of 12 azimuth

[1] Weibull distribution is a statistical probability function which is often used in wind energy studies. It is used to model wind speed variations for a given site. The Weibull distribution curve has two parameters, one is for shape of

sectors, the number of roughness changes (Rch), the effects of obstacles and the terrain, the resulting Weibull parameters (A and k) and the frequency of occurrence (%) are given. The effect of obstacles is given as the reduction in percent of the wind speed in each sector. The speed-up/retardation and turning of the wind calculated by the complex terrain mode are given in per cent and degrees, respectively.

The right-hand column in the result display gives the sector-wise distribution of the total energy content of the wind or the actual power production by a wind turbine, in per cent. The heading of the display shows the names of the wind atlas data set and site description employed, as well the height for which the calculations are performed.

Askervien Hill Wind Data, 1982-1983 2/11/95 19:41

Roughness Length = 3 cm. Height: 10.0 m a.g.l.

Sect	Rch	Input		Obstacle	Orography			A	k	%	E%
0:	0	0.0%	0°	0.0%	51.5%	13°	:	8.8	8.85	0.0	0.0
30:	0	0.0%	0°	0.0%	88.1%	4°	:	7.7	4.38	0.0	0.0
60:	0	0.0%	0°	0.0%	69.3%	-11°	:	6.1	3.94	3.1	0.7
90:	0	0.0%	0°	0.0%	33.9%	-12°	:	6.9	2.82	6.8	2.3
120:	0	0.0%	0°	0.0%	19.6%	-2°	:	11.3	9.02	3.3	4.3
150:	0	0.0%	0°	0.0%	23.8%	8°	:	10.7	4.51	6.8	7.6
180:	0	0.0%	0°	0.0%	51.5%	13°	:	9.7	3.12	10.5	9.3
210:	0	0.0%	0°	0.0%	88.1%	4°	:	11.5	3.76	27.8	39.8
240:	0	0.0%	0°	0.0%	69.3%	-11°	:	10.1	4.56	16.9	16.0
270:	0	0.0%	0°	0.0%	33.9%	-12°	:	9.9	4.96	19.3	17.0
300:	0	0.0%	0°	0.0%	19.6%	-2°	:	8.5	8.85	5.0	2.8
330:	0	0.0%	0°	0.0%	23.8%	8°	:	8.5	8.85	0.5	0.3
M= 9.2 m/s		E= 610. W/m²						10.2	3.59		

DATA OBSTACLE ROUGHNESS OROGRAPHY ATLAS WECS HEIGHT
DISPLAY RESOURCEFILE FREQUENCY DOS HELP RETURN STOP
WAsP>

Figure 2.4. A typical result display of WAsP.

the distribution and the other is for scale. The shape parameter (k) describes the variations in wind speed and (A) is the wind speed. The bigger the (k), the less variations in wind speed – the Weibull curve has sharper peak.

CHAPTER III

APPLICATION OF WAsP TO A SIMPLE ISOLATED HILL

3.1 INTRODUCTION

In order to gain experience with the WAsP software and as a first step in the evaluation of its capabilities, the wider range of data from the Askervein Hill field experiments was used for validation of the WAsP predictions in a similar manner to Troen [23].

The physical process that governs the mean wind flow and turbulence characteristics over a simple isolated hill under a variety of atmospheric conditions have been the subject of many studies and investigations. Successful empirical techniques such as that of Taylor and Lee [5] and others have been developed to estimate the mean wind and extreme gust speeds at sites in complex terrain for the design of wind sensitive structures. These techniques were followed from the analytical work of Jackson and Hunt [6] and the extensive field work carried out by the Askervein Hill project team. However, in most cases, these models have managed to cope only with strong, neutrally stable and attached wind flows over a simple low and isolated hill.

3.2 ASKERVEIN HILL PROJECT

The Askervein Hill project was a collaborative study of boundary layer flow over a low hill carried out under the auspices of the International Energy Program of R&D on Wind Energy Conversion Systems (WECS). Two field experiments were conducted during September-October 1982 and 1983 on and around the Askervein Hill. The main objective was to further investigation of boundary layer flow over relatively low hills, especially in relation to WECS siting. Factors of particular significance include the mean wind speed-up and the modification to the turbulence which occur as air flows over a hill.

3.2.1 Askervein Hill site details

Askervein hill is located near the west coast of South Uist Island in the Outer Hebrides of Scotland. The hill coordinates are 57° 11' North and 7° 22' West. Its relative height is about 116m above the surrounding flat terrain; this point is called hill centre (CP). It is essentially elliptical in plan form with a 1km minor axis and a 2km major axis oriented along a generally NW-SE line. The highest point (HT) on the hill is at 124m above flat terrain. This site was chosen as it was quite central to all participating countries and more importantly, it is well isolated with uniform surface texture. The predominant wind regimes during September and October are SW (right angle to the major axis) and S at the nearest meteorological station (Benebecula). Moderate to strong winds are the norm at that time of year.

To the south west there is a flat uniform fetch of about 3-4Km to the coast line. The ground cover is mostly heather, grass, low scrub and some flat terrain. Figure 3.1 and 3.2 show the pictorial and contour map of the hill.

Figure 3.1. The pictorial view of the Askervein Hill from South West.

Figure 3.2. Askervein Hill and the surrounding terrain.

3.3 ASKERVEIN HILL WIND CLIMATE

3.3.1 Wind data collection

During two experiments data were collected from over 50 towers which were deployed in approximately linear arrays through CP and HP. The main lines chosen were oriented at 43° and 133° (grid) NE-SW and SE-NW along the minor and major axis of the hill. These lines are shown in Figures 3.3 and referred to as lines A, AA, and B.

Locations along these lines are denoted by a code which includes the line identifier (e.g. A), the direction (e.g. SW) and the horizontal distance from HT (or in the case of line AA only from CP) in tens of meters. The majority of towers were simple 10m posts bearing cup anemometers.

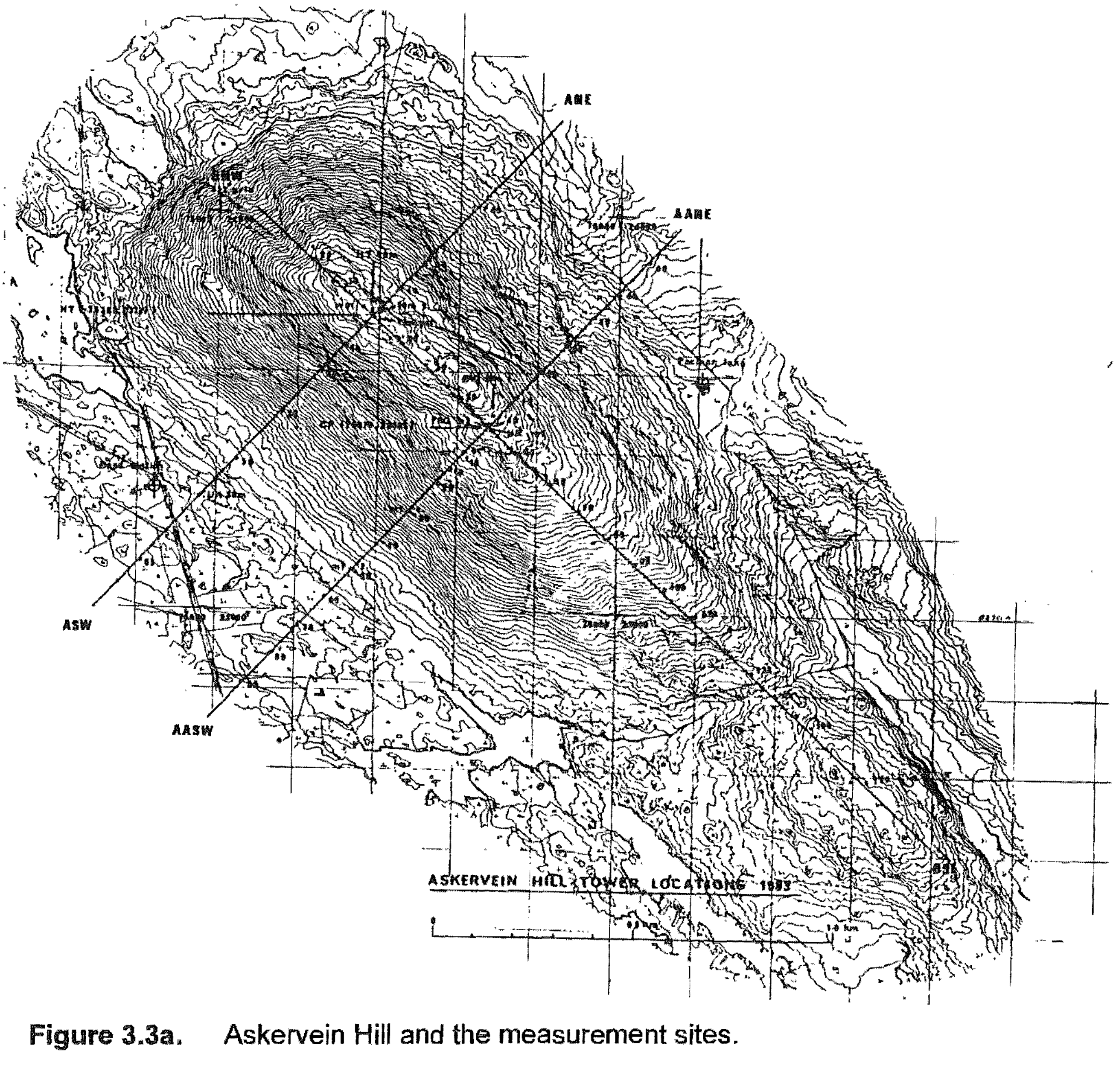
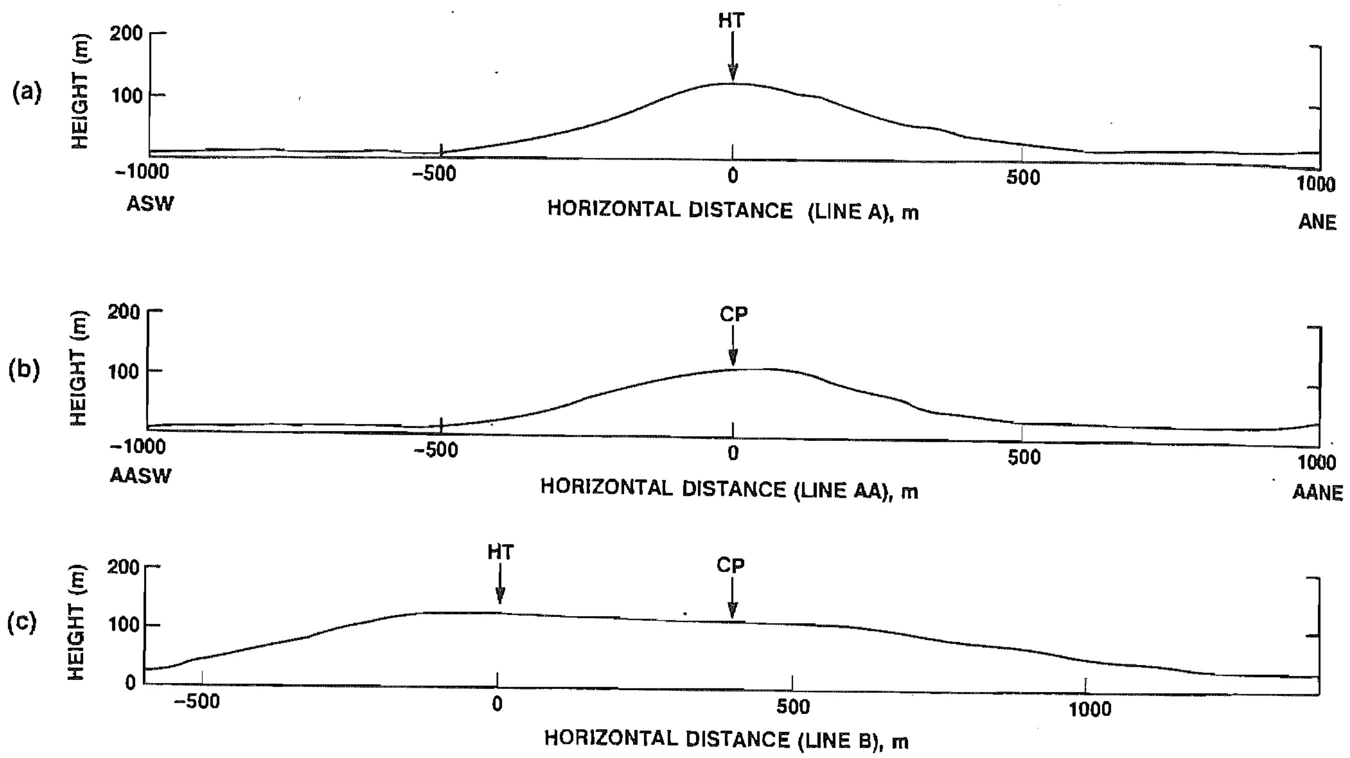


Figure 3.3a. Askervein Hill and the measurement sites.



Topographic cross-sections through the hill, no vertical exaggeration. (a) Along line A. (b) Along line AA. (c) Along line B.

Figure 3.3b. Topographical cross-sections through the hill.

3.4 APPLICATION OF WAsP TO THE ASKERVEIN HILL

3.4.1 Input Data

3.4.1.1 Terrain Map

A pre-digitised height contour map of the Askervein Hill was first obtained. The map format was different from the one specified by WAsP. It also contained more than 16,000 data points - a limit set by the WAsP Orographic model. A computer program written in Turbo C+ was designed to re-format and trim the file as required. The final map contains 15,375 points with 2m contour intervals from HT down to 90m height and then 4m intervals down to flat terrain. The original map did not contain height contours for the Reference Site (RS). Several attempts were made to use the digitising facility within WAsP to include height contours of the RS. Unfortunately, it didn't work. The WAsP Orographic model would recognise the RS coordinates even if it is not included in the map since it uses a universal mapping coordinate system. However, later on in the course of this study, it was discovered that absence of reference site height contours from a terrain map would yield to erroneous Wind Atlas calculations for a site on that terrain. A simple but sufficient method was devised to correct this problem and the Askervein Hill analysis was modified to overcome this problem. This method is fully explained in chapter 4 (see Figure 3.4). Note that in Figure 3.4 there are some unclosed contour lines. WAsP is not troubled by them. Figures 3.5 to 3.7 show WAsP generated contoured views of the hill from 235°, 180°, and 270° directions. Note for all these maps:

- they are NOT TO SCALE;
- graphical shadings do not represent the surface texture on the hill. They reflect the congestion/separation of the height contours after being imported from WAsP to the word processing software.

Later, WAsP results are compared with the field data at these wind directions.

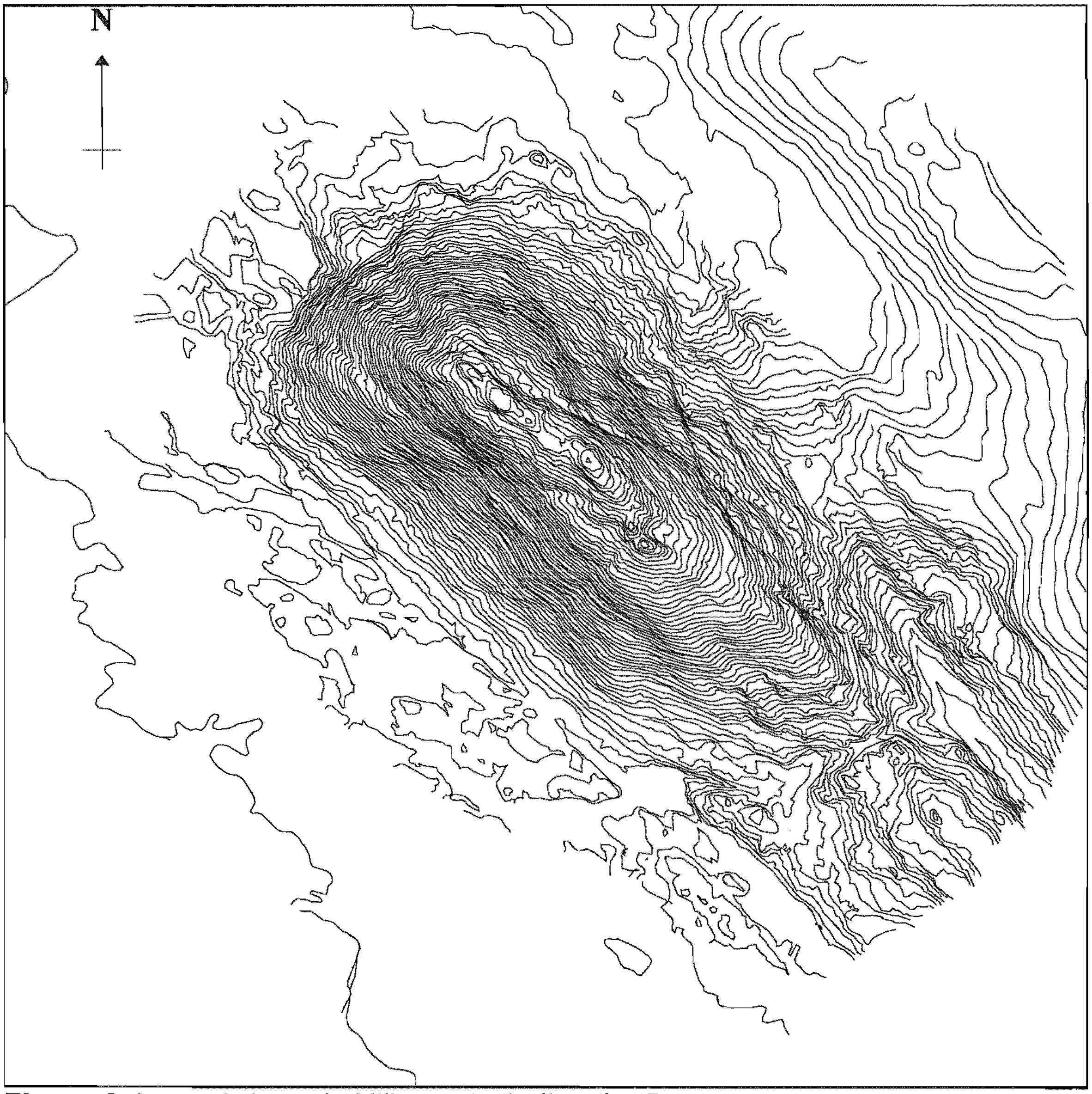


Figure 3.4. Askervein Hill map including the RS.

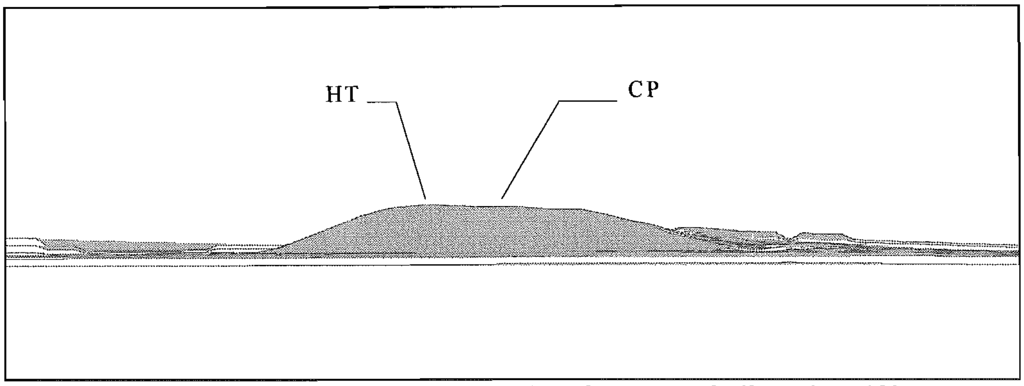


Figure 3.5, View of the Askervein looking from 235° direction (SW).

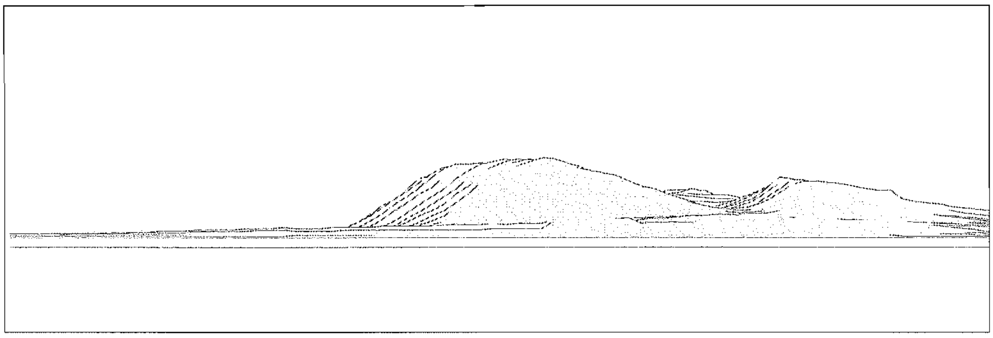


Figure 3.6. View of the hill looking from 180° direction (South).

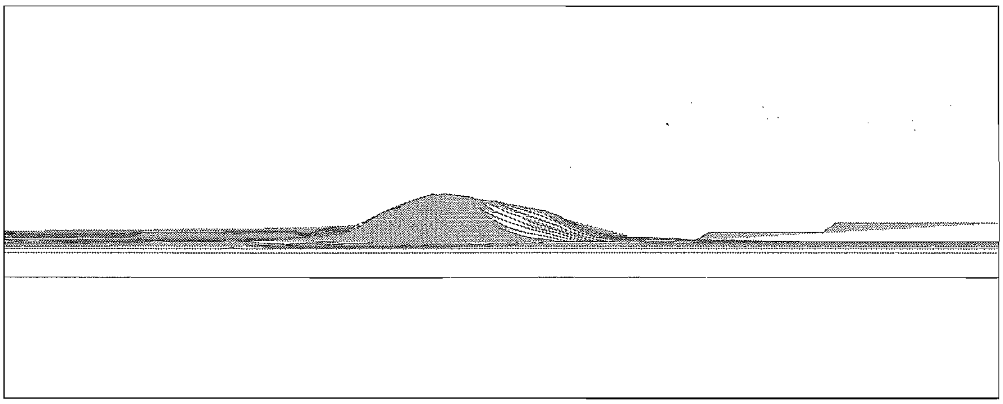


Figure 3.7. View from 270° direction (west).

3.4.1.2 Wind speed data from RS

The mean wind speeds and directions measured during the 1982 and 1983 field experiments (Taylor et. al, [24]) are tabulated into two meteorological tables, one for each year. These wind data designate mean flow runs at RS at the pole height of ΔZ=10m. These tables are compiled as specified by WAsP into one table, See Figure A2.1 in Appendix A2.

Although these data are for a short period, they will be sufficient to provide a reference for the mean wind speeds for sites over the hill. In addition, in this study wind speed-ups caused by terrain features are the main interest and WAsP derives them directly from the map data file, independent of the input wind data.

3.4.1.3 Surface Roughness Length

The equivalent full scale roughness length over the whole area was considered to be 3cm from the full scale test. This proved to give satisfactory results. The hill and adjacent terrain are covered by grass, heather and low scrub. This value has been widely used in all subsequent full scale and wind tunnel studies of the Askervein Hill. Also, the RS velocity profile is essentially logarithmic with $Z_0 = 0.03$m.

3.4.1.4 Obstacles at the RS

After investigating through photographs of the reference site it was decided to model it with no obstacles. Dr. A. J. Bowen (project supervisor) who was one of team members in the Askervein Hill Project also confirmed this decision.

3.5 PROCESSING INPUT DATA AND RUNNING THE WAsP PROGRAM

Once all required input data are prepared, the WAsP program is employed to predict wind flow conditions at each site on the hill. This requires execution of the WAsP orographic model for each individual site and storage of output. This proved to be a tedious task since there are over 70 sites and each operation takes over a minute. Hence, a batch file was prepared to do the task automatically. In batch mode the input to WAsP comes from an ASCII disk file rather than a keyboard. The input file contains commands and input data in exactly the same format and order as it would have been given in interactive mode. See Appendix A3.

3.5.1 Summary of results

WAsP calculated speed-up values are tabulated in Table A1.1 in Appendix A1 for all the sites on and over the hill for certain wind directions. Each site is referred to by its location designation number. Comprehensive WAsP calculations for each site are given in Appendix A4.

3.5.2 Normalised wind speeds

In the original study of the variations in mean wind speed at fixed height over the hill, Salmon et al. [25] plotted normalised wind speed ($\Delta S + 1$) along AA, A, and B lines. These plots were the only available sources of observed fractional speed-up values for Askervein Hill to this research. Therefore, WAsP results are presented and compared with the field data in similar fashion. Figures 3.8 to 3.10 represent normalised wind speeds at ΔZ=10 m along AA, B, and A lines.

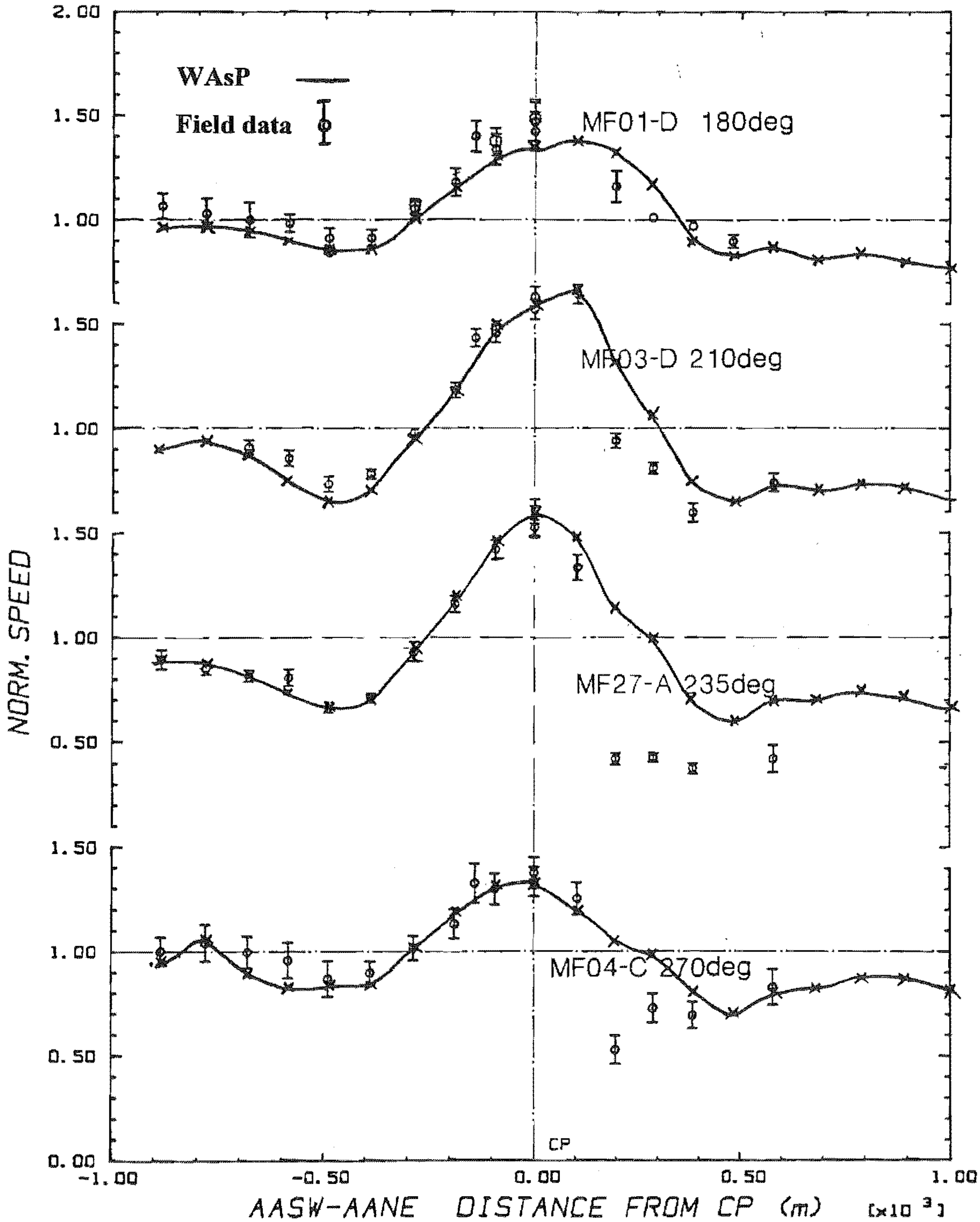


Figure 3.8. Plots of predicted normalised wind speed at Δz=10m compared with the field measured data, along AA line.

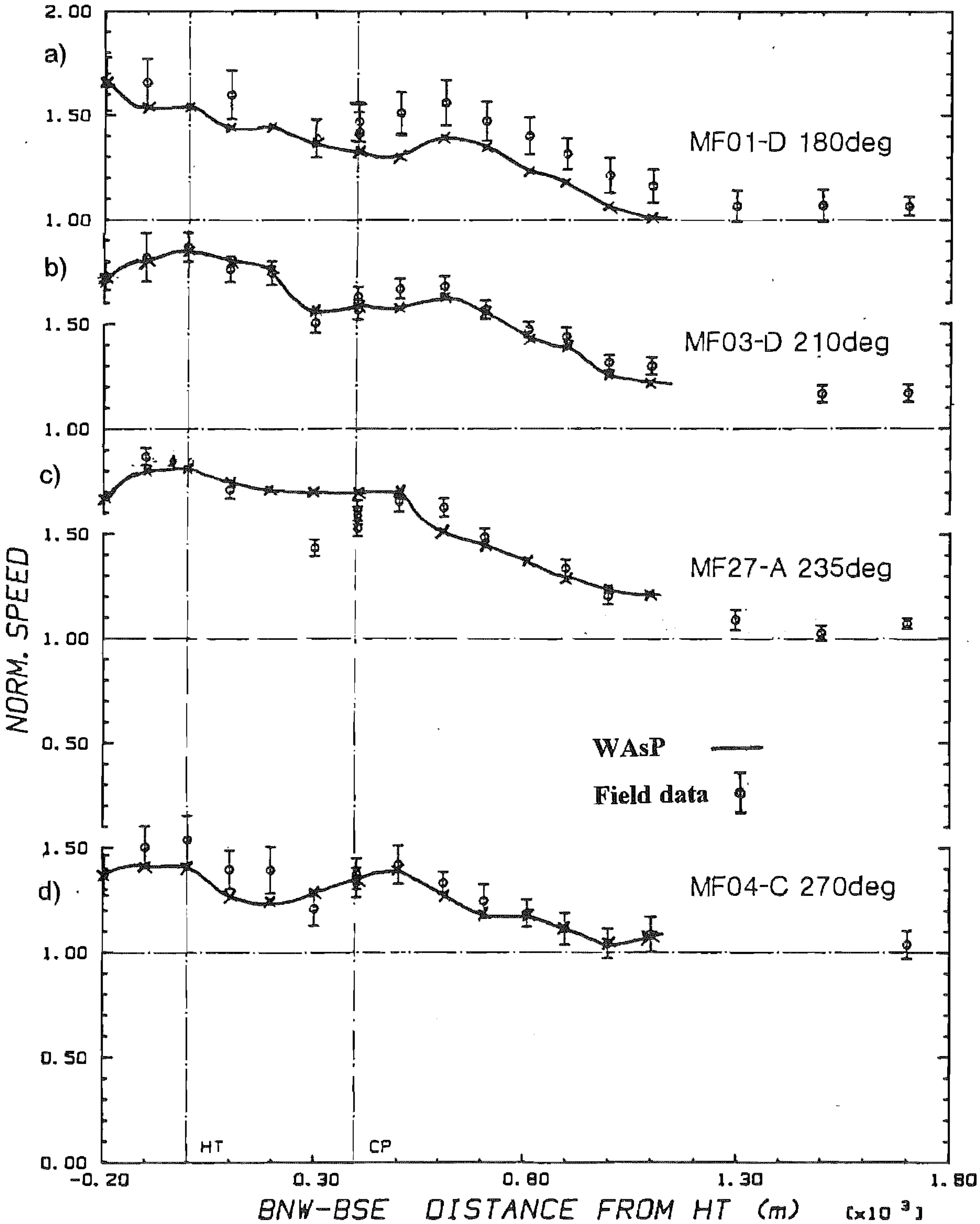


Figure 3.9. As Figure 3.8 but along line B.

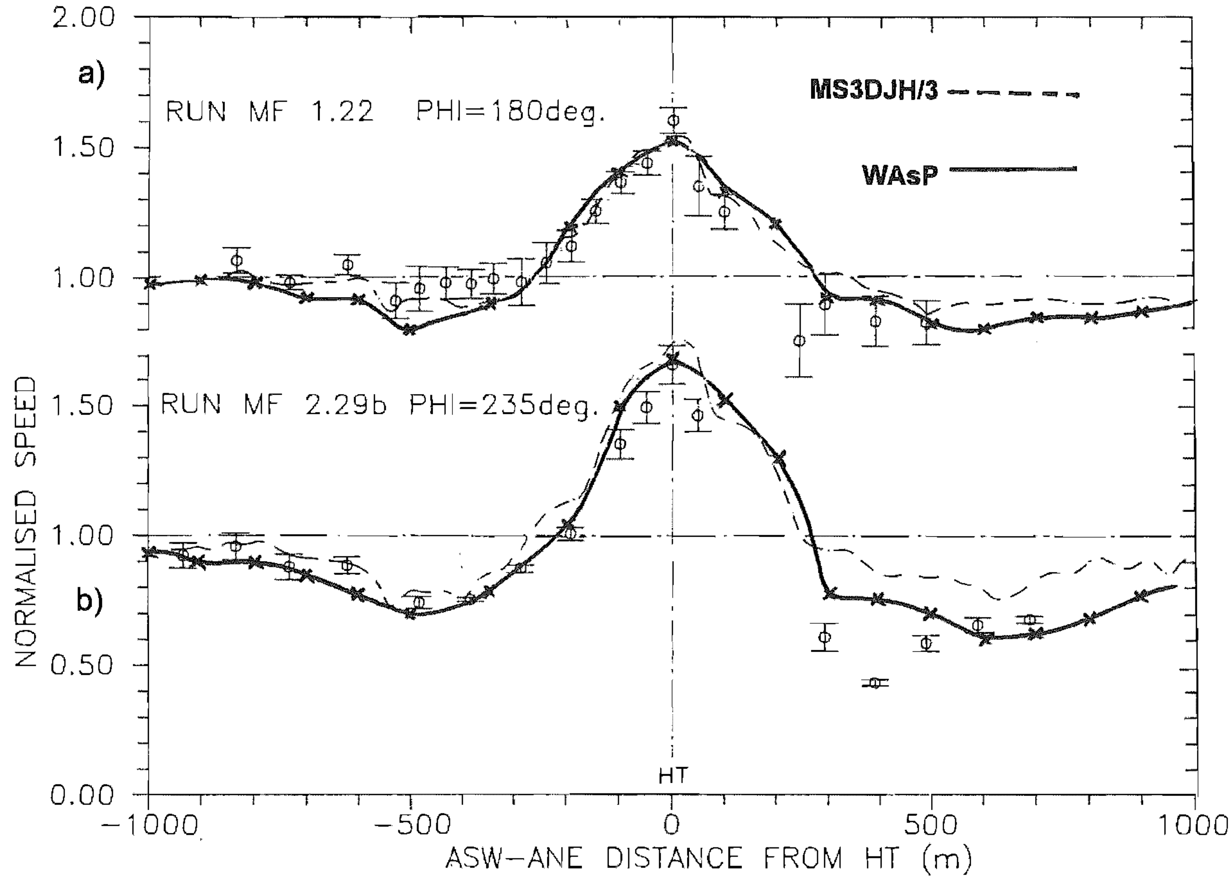


Figure 3.10. As Figure 3.8 but along line A.

3.6 DISCUSSION OF RESULTS

Figure 3.8: illustrates plots of WAsP predicted normalised wind speed compared with the field results along the AA line. WAsP predictions are remarkably close to the measured data on the upwind side and over the summit of the hill. It is even more encouraging to see that WAsP has picked up the partial wind stagnation on the upwind side of the hill. This feature is seen for all displayed wind directions, in particular, 235° sector with the wind direction approximately perpendicular to the major axis of the hill. The field data revealed less pronounced upwind partial stagnation for 180° direction and WAsP prediction clearly reflects the same observation.

WAsP, similar to other numerical models, fails to cope with the substantial wind speed reduction in a wake region in the lee side of the hill. This is because WAsP assumes neutrally stable and attached flows in wind speed-up calculations and tends to overestimate wind speeds in the lee side where the presence of turbulent and unattached flows are highly possible. Again, 235° direction clearly illustrates the overestimation by WAsP for this region. For other directions in the lee side where the relative steepness (ground slope in the direction of prevailing wind) reduces, WAsP tends to predict speed-up values closer to the observed data. This is visible for 180° and 135° directions where WAsP lee side estimations are almost in the range of measured data.

Figure 3.9: contains plots of normalised wind speed ratio along the B line over the hilltop ridge. WAsP agreement with the field data is excellent. In graph b), c), and d), WAsP predictions are consistent with observed data for all sites. For 235° direction (hill major axis is perpendicular to the wind), WAsP clearly picks up the pattern right down to the last few sites in the southeast direction.

The BSE30 location (100m to the northwest of CP), however, appears to exhibit consistently lower wind speeds than those observed at the tower locations to either side (CP and BSE20) for all shown directions. This behaviour is not picked up by WAsP or other previous numerical models and wind tunnel studies, Teunissen et al [26]. It is thought that this is probably due to small scale, local, topographic variations in this area which have been slightly smoothed in the models. However, the possibility of errors due to anemometer and data-logger problems (Salmon et al [25]) can not be ruled out.

In graph 3.9(a), where wind direction is from the south (i.e. 180°), the wind speeds along the hilltop ridge appear to be underestimated by the WAsP model in comparison with the field data. This contrasts with the good agreement for 180° direction in Figure 3.8, graph (a). In selecting field data for 180° direction group average, Salmon et al [25] admits that, two anemometer reading runs (MF26-A and 01-D) were excluded since they had $|R_i| > 0.015$. The direction group was then formed from runs MF01-E and MF04-A. Both of these, and especially MF01-E, had high observed hilltop ΔS in comparison to the excluded cases. Therefore, this discrepancy is caused more by the slight anomaly in the 180° group-averaged data and WAsP predictions are felt to be adequate.

The normalised wind speed ratio exceeds 1.5 over a substantial (~1km) length of the hill top ridge with a maximum about 1.85 (WAsP estimation is 1.88) at the hilltop (HT) itself. WAsP ability to predict these values adequately along the ridge is great news for users of wind energy where low hills are predominant in many countries such as Europe away from the Alps - for which the WAsP program was originally developed.

Figure 3.10: Normalised wind speeds along the A line show similar characteristics to the line AA results. The comparisons are in excellent agreement on the upwind side and over the hilltop. For the 235° direction WAsP precisely predicts the upwind partial stagnation and - as in previous cases - fails to cope with the highly turbulent and separated flows in the lee side of the hill. It over-estimates wind speeds at this region but it later picks up the pattern at ANE50 and ANE60 locations.

The WAsP results for 180° direction are also encouraging. For this direction, Askervein Hill presents a fully 3-dimensional low hill example to the flow and WAsP adequately handles wind speed variations; even in the lee side satisfactory predictions are produced.

3.7 VERTICAL WIND PROFILES AT THE HILL TOP (HT)

Full-scale vertical wind profiles at hill top for different wind directions have been studied and compared with wind tunnel simulations by Teunissen et al [26]. Table A1.2 displays wind speed-up values at hill top for different sectors to heights up to 100m as calculated by WAsP.

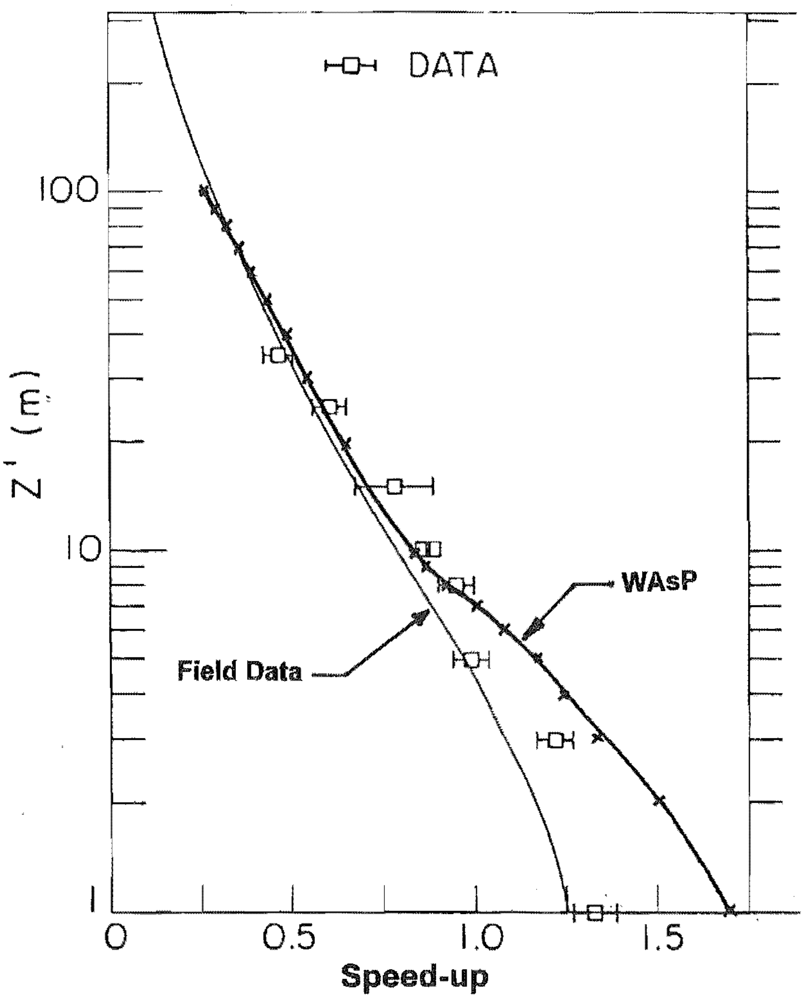


Figure 3.11. Hill top velocity profile calculated by WAsP compared with the full-scale data for 210° sector.

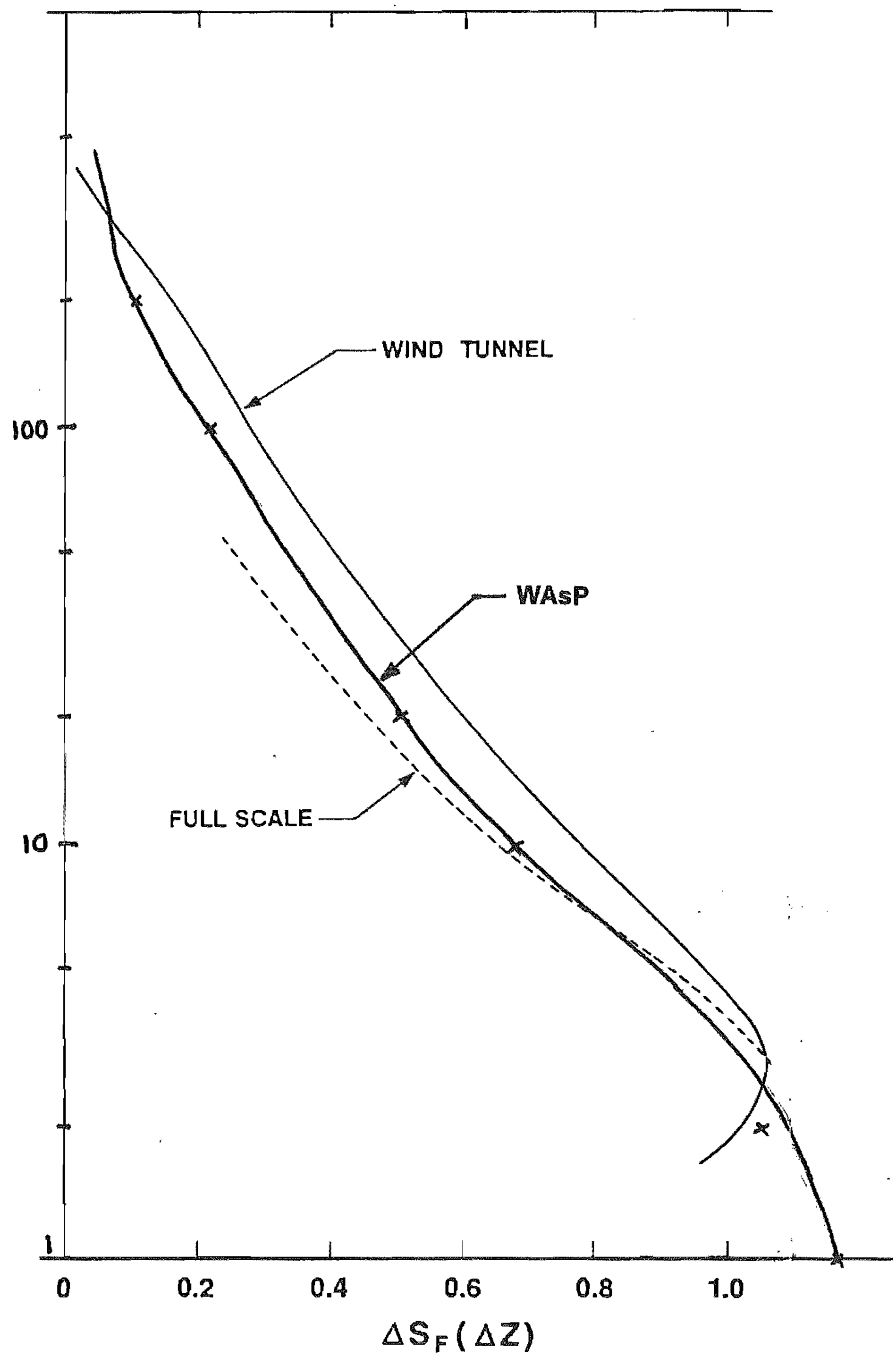


Figure 3.12. Predicted hill top velocity profile compared with the full-scale and wind data for 235° sector.

In Figure 3.11, the hill top velocity profile calculated by WAsP has been compared with the full-scale data for 210° sector. The estimated profile by WAsP is seen to agree quite well with the full-scale measurements. Maximum speed-ups in field measurements occur very close to the surface ($\Delta Z \approx 1$-3m) and reach over 100% for this wind direction. Theoretical considerations (e.g. Taylor and Lee [5] and Taylor et al [24]) suggest that these maxima should occur at the surface, as implied by the full-scale profile. Since the WAsP program ignores separation and turbulence near the surface in its speed-up calculations it predicts maximum values very close to the ground, e.g. $\Delta Z \approx 0.01$m. This is immaterial for WECS siting applications as wind turbines harvest winds at heights well above the internal boundary layer depth; i.e. ΔZ >20m.

Results from wind tunnel simulation of the Askervein Hill by Teunissen et al [26] - the AES results in particular, are in good agreement with the full-scale data and hence with the WAsP predictions, see Figure 3.12. This confirms the correct investigation reported here. The wind tunnel and full-scale profiles, unlike the WAsP results, display an apparent maximum in ΔS (1.1 for AES run and 1.3 for full-scale) at $\Delta Z \approx 3$m. The maximum near-surface ΔS values can be compared with the prediction of the simplified rule-of-thumb suggested by Jackson and Hunt [6] for flow over two dimensional low hills of gentle slope - i.e. $\Delta S_{(max)} \approx 2h/L$, where h is 116m and L is 215m for this wind direction. This relationship yields a value of $\Delta S_{(max)} \approx 1.15$ which is in agreement with values in Figure 3.12.

On the other hand, the observed depth '*l*' of the inner boundary layer - if it is interpreted as the height at which the absolute velocity increases (ΔU) is a maximum - is about 3 m from WAsP predictions. The relationship suggested originally by Jensen et al [27] and again by Mason and King [28] (i.e. $\ln^2(l/z_0) \approx 2k^2L$) yields a value of $l \approx 3.3$; a good agreement. Unfortunately, only the velocity profiles of 235° and 210° directions were available and other direction profiles would have made the comparison more comprehensive. However, results from above comparisons indicate that WAsP prediction of wind speeds at heights above the internal boundary layer length - i.e. ΔZ>10 m is fairly reliable; and indeed this is the region with which all wind turbine siting assessments are concerned by.

Figures 3.13 to 3.16 show vertical velocity profiles at HT calculated by WAsP for selected wind directions.

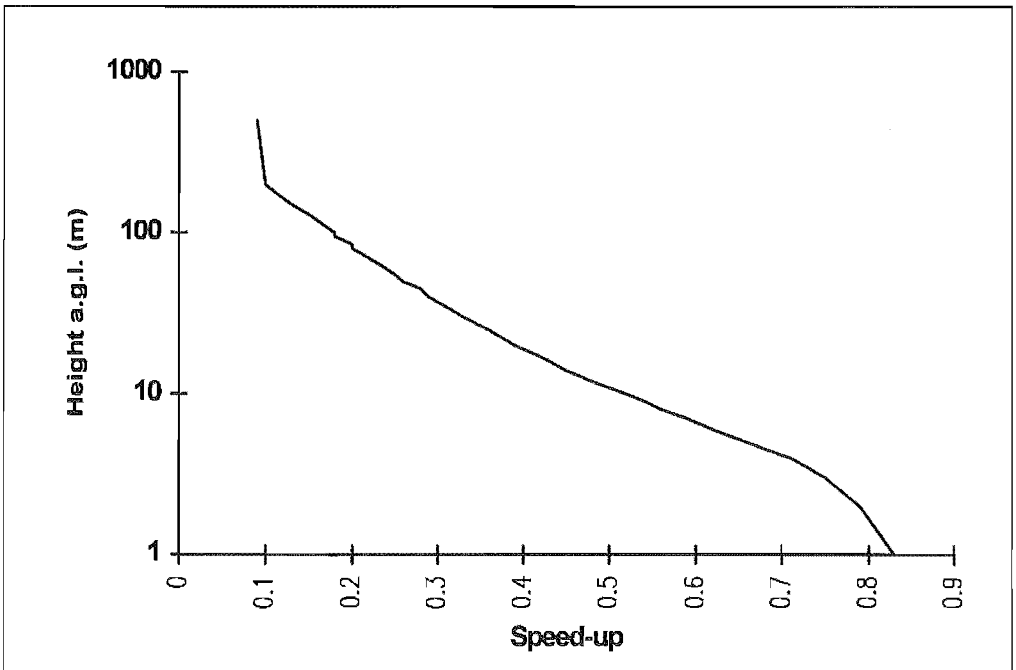


Figure 3.13. Vertical wind profiles at HT for 180° wind direction.

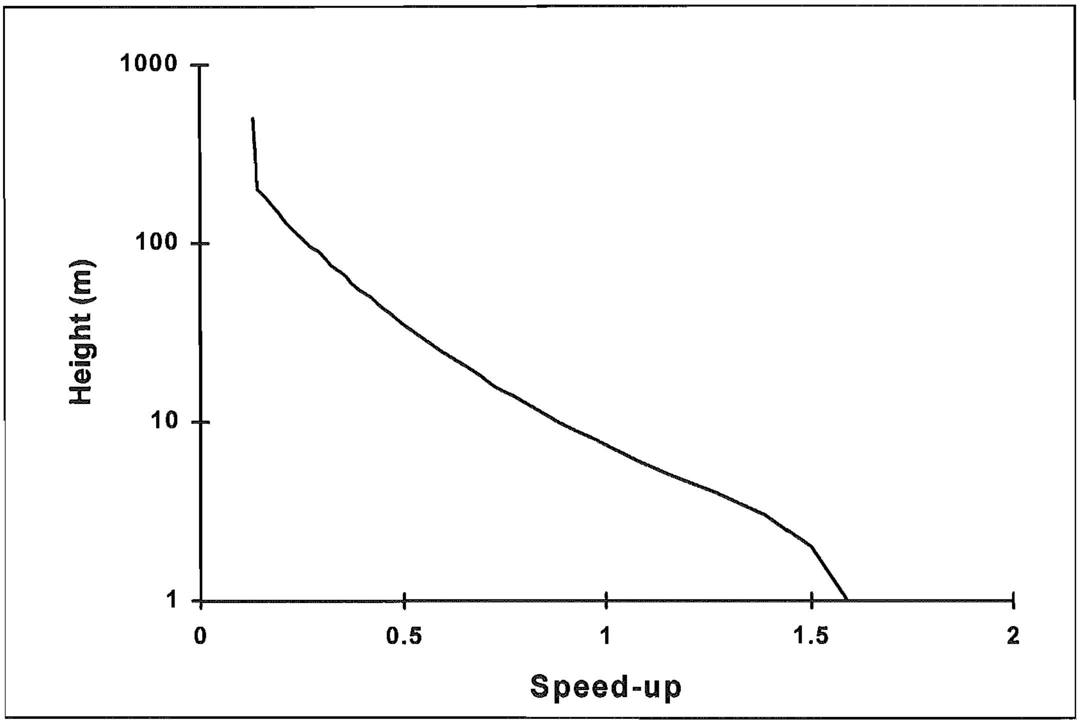


Figure 3.14. Vertical wind profiles at HT for 210° wind direction.

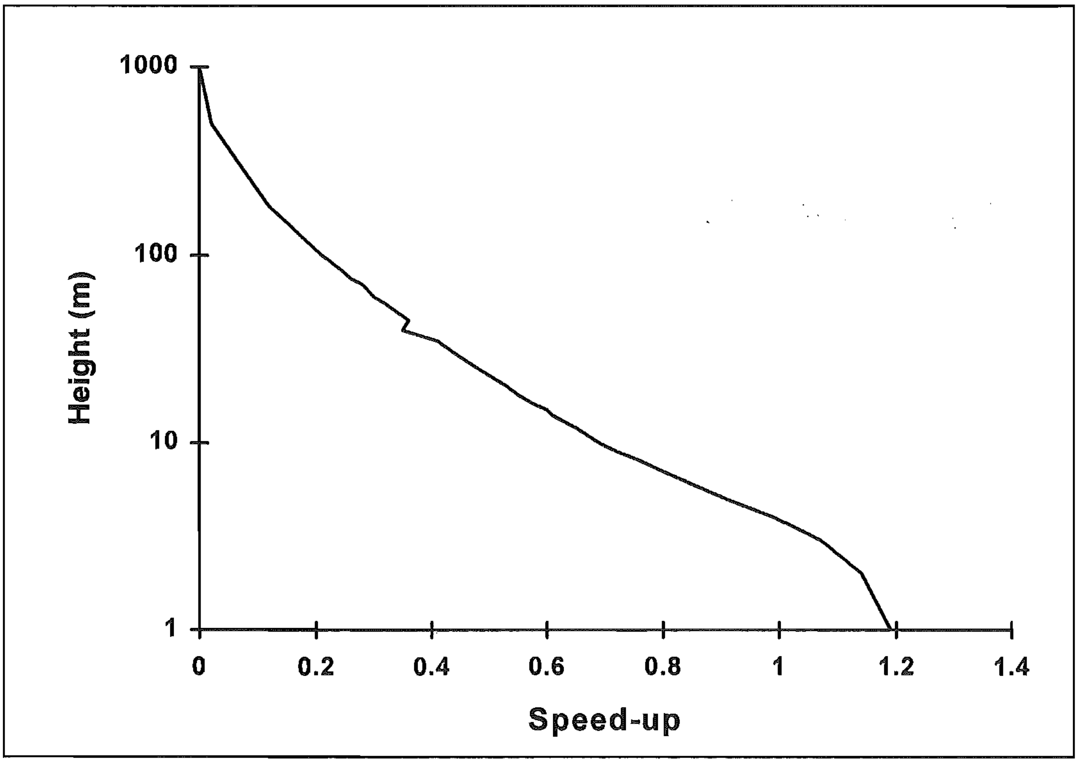


Figure 3.15. Vertical wind profiles at HT for 240° wind direction.

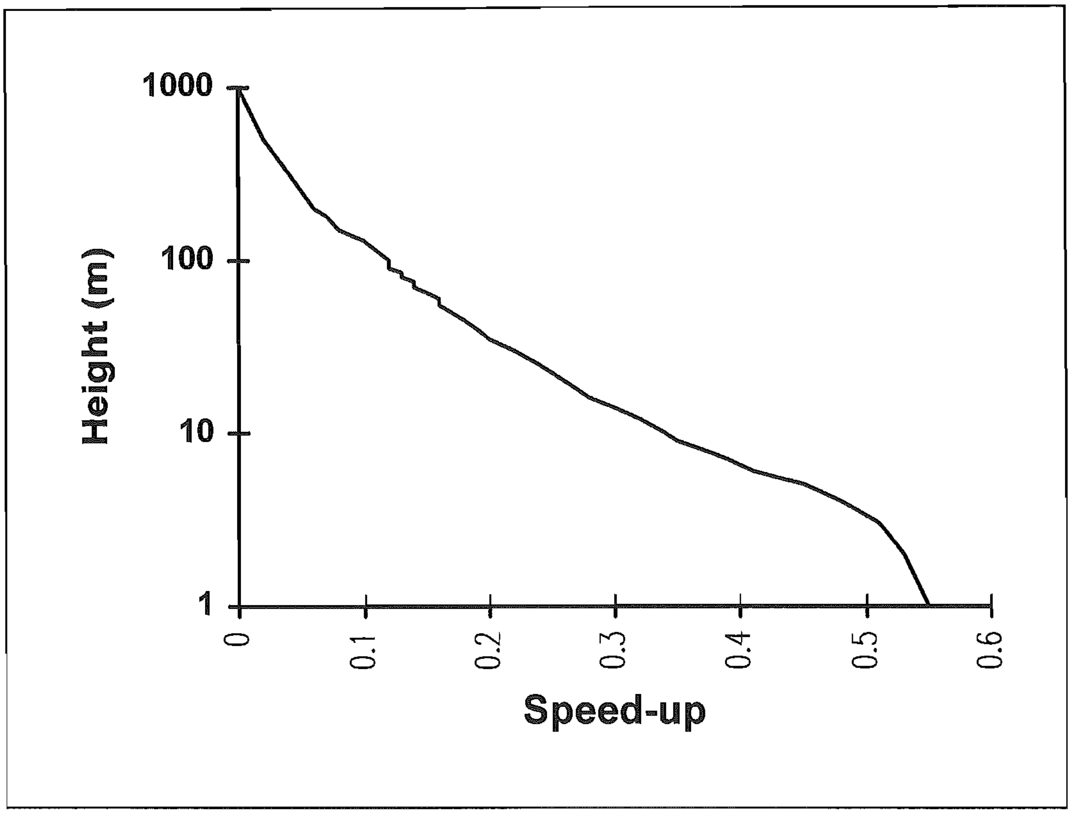


Figure 3.16. Vertical wind profiles at HT for 330° wind direction.

3.8 Conclusions

The exercise of applying WAsP to Askervein Hill provided an excellent opportunity to gain experience with the software and to evaluate its capabilities. WAsP prediction of wind speed-ups due to local terrain on the upwind and over the summit side of the hill are in excellent agreement with the field data. It clearly and adequately picks up both the upwind partial stagnation and the acceleration of the wind over the ridge top. However, it is unable to reliably predict wind speeds in the lee side of the hill where the flow is highly turbulent and separated - the 'wake' region. This inadequacy is more pronounced for 235° direction where wind direction is perpendicular to the major axis of the hill. For the 180° direction, the model predictions fall just within the range of observed data.

WAsP also predicts wind speeds adequately for the wind directions where the hill is representing a fully 3-dimensional topographical feature, e.g. 180° direction along the AA and A lines.

CHAPTER IV

APPLICATION TO COMPLEX TERRAIN

4.1 INTRODUCTION

Information on the general wind characteristics of a geographical region is a prerequisite for considering the utilisation of wind power at a site. Climatological data gathered at area weather stations (usually located on flat open terrain) will often provide information concerning wind speed, direction, duration, turbulence, etc., over a number of years. However, if the area in which wind power installations are to be made includes hilly country, an obvious desire is to choose sites on or near the top of hills or ridges. This would enable benefits to be gained from the faster moving stream of air which results from compression of streamlines near the summit. Therefore, it is vitally important to be able to correlate wind behaviour approaching a terrain feature and the terrain topography with the character of flow at a prospective site.

This chapter compares WAsP predictions to actual field measurements for a typical hilly terrain for New Zealand - the Port Hills of Christchurch. The WAsP program is designed for terrain with gentle slopes. Its User's Manual admits that the orgraphic model produces erroneous predictions when it is applied to steep hills and ridges with slopes greater than 30% [21]. The Port Hills are steep and lie outside the WAsP envelope. Because it has valuable field data, it was a unique opportunity to test WAsP outside its envelope and assess the errors - leading to the next chapter which these errors are analysed by a utility software called RIX.

4.2 CRITERIA FOR SELECTION OF THE REGION TO BE STUDIED

New Zealand and many other countries with an appreciable wind energy resource have a common WECS siting problem. They are all geographically complex but there are very few of these sites with field data. However the Port Hills of Banks Peninsula enjoy recorded long term and reliable meteorological data. This area is chosen for several reasons:

- The area is fairly complex and contains typical features of a hilly terrain; e.g. includes a saddle with its well known channeling effect on the NE and SW winds.
- The area is surrounded both by flat open farm land and sea.
- There are both long term and reliable wind data recorded at Christchurch Airport which is situated on the open, flat Canterbury Plains about 15km NW of the Port Hills. Additional wind reference data are also available from the Lincoln University climate station.
- There is a great deal of published field data for sites in this area. This area has been the focus of attention by the Wind Energy Resource Surveys of New Zealand; [30] and [31].
- The surface texture is fairly uniform throughout the area.
- Some of these sites have the greatest practical potential for wind energy farming, e.g. Gebbies Pass.
- Existence of comprehensive wind tunnel study data for this area. Detailed full scale and model investigations of the wind structure of the Gebbies Pass area studied by Neal [33] and Neal et al [32].
- Proximity of the Port Hills to flat terrain and easy access from Canterbury University.

4.3 TERRAIN CHARACTERISTICS OF THE PORT HILLS

4.3.1 Regional topography[1]

This region is an isolated group of old volcanoes neighbouring the Canterbury Plains near Christchurch. Its area is about 25km square containing many smooth rounded ridges radiating outwards from the two volcanic centers of Lyttleton and Akaroa Harbour, see Figure 4.1. The Port Hills are situated close to Christchurch City from the western rim of Lyttleton Harbour.

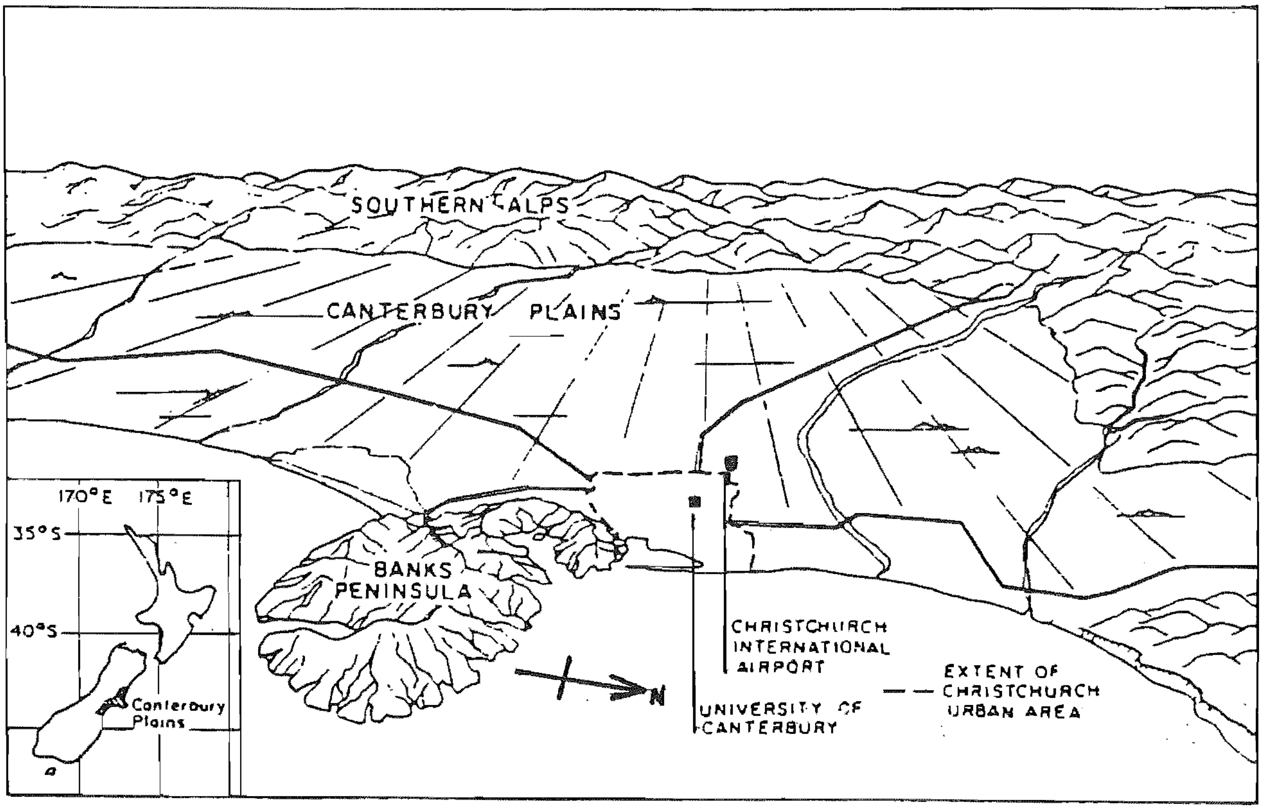


Figure 4.1a. Oblique view of Banks Peninsula, Canterbury Plains and Southern Alps [34].

[1] Extracts from Smyth [34].

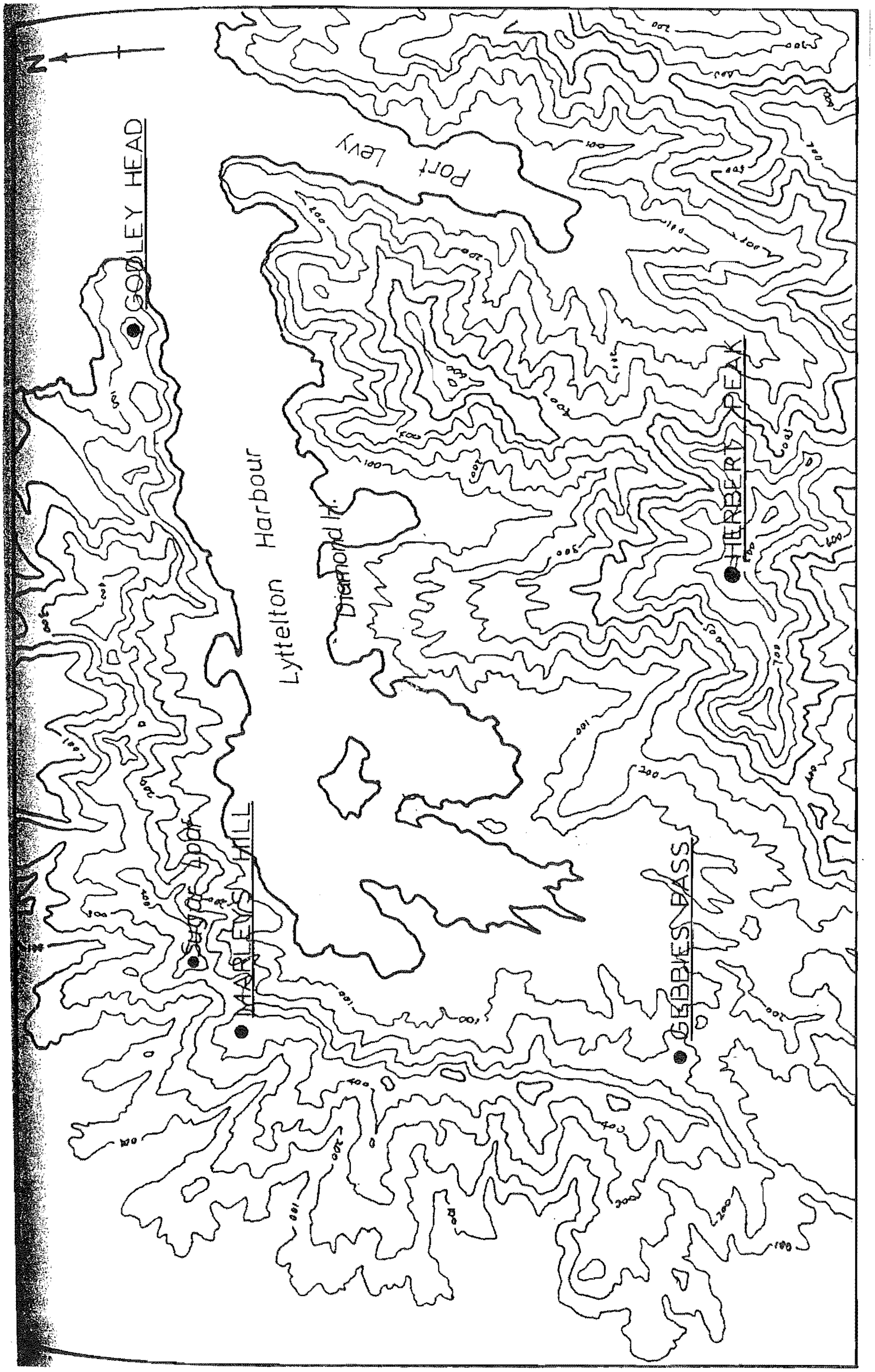


Figure 4.1b. Sites on the Port Hills [34]; Gebbies Pass (275m), Mt. Herbert (917m), Sugar Loaf (496m), Godley Head (245m), Marley's Hill (502m).

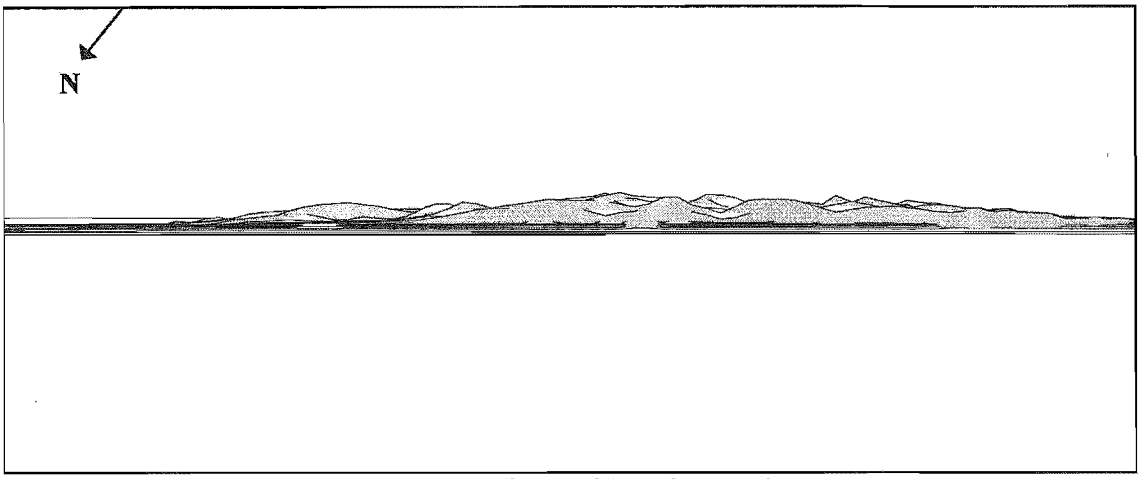


Figure 4.1c. View of the Port Hills looking from Christchurch Airport, generated by WAsP.

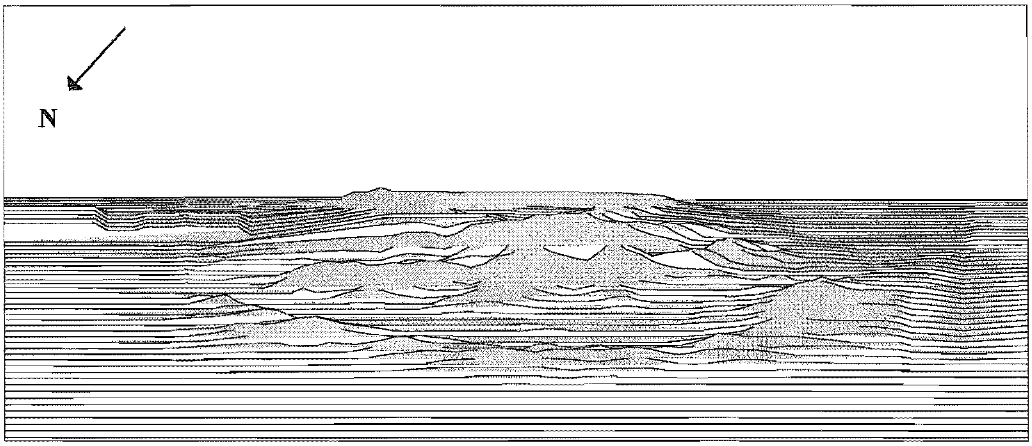


Figure 4.1d. As Figure 4.1b, but from a camera height of 10000m.

As an isolated elevated area, the Port Hills are very well exposed to all the wind directions and as rounded terrain the wind is enhanced as it flows across the ridges. The main ridge curves around the Lyttleton Harbour for about 20km and is typically 400m high with steep rugged slopes on the E-SE side facing the harbour and more gradual and smooth slopes on the NW side facing Christchurch City. The terrain is varied with the lower slopes overlooking the city used for residential housing and the upper slopes covered with bare grass interspread with rocky outcrops and occasional stands of trees. The Port Hills are bordered on the eastern side of Lyttleton harbour by the higher hills of Banks Peninsula that rise to about 900m around Mount Herbert. The terrain immediately to the west of the Port Hills comprises the flat Canterbury Plains with the city of Christchurch and the adjacent Pacific Ocean to the north and south.

4.3.2 Site description and wind data collection

There are five sites in the Port Hills area, namely: Gebbies Pass, Mount Herbert (also known as Herbert Peak), Sugar Loaf, Marley's Hill, and Godley Head which have been the focus of several Wind Energy Resource studies. A brief description of each site and the nature of its meteorological data are discussed. Wind data for all these sites except Sugar Loaf were obtained from field measurements taken by Smyth [34]. These measurements were made using standard Lambrecht Cup anemographs over a continuous six month period from June to November 1981. Additional field data of of various record lengths and conditions are also available from the compiled statistics reported by Cherry and Smyth [30] and [31].

4.3.2.1 Gebbies Pass (275m a.m.s.l.)

The pass is relatively low at 150m elevation (a.m.s.l.) and adjacent hills reinforce the channeling of most winds along the harbour axis making it unusually windy. However, it is sheltered from the NW winds which occur over a significant proportion of the time. The pass region would be the most likely of the sites to be of interest for wind turbine site development. The anemometer was mounted on a 10m pole on a smooth hill on the NW ridge overlooking the pass. Hourly wind speeds and directions were collected during the 1981 (June - November) survey. Although the terrain is quite complex, it is generally smooth and rolling, and winds blowing over the pass in either direction can be expected to be fully attached apart from limited pockets of separated flow in sheltered areas. See Figure 4.2.

Figure 4.2a. View from highest point in Gebbies Pass looking to the NE.

Figure 4.2b. View as in 4.2a but looking to the SW.

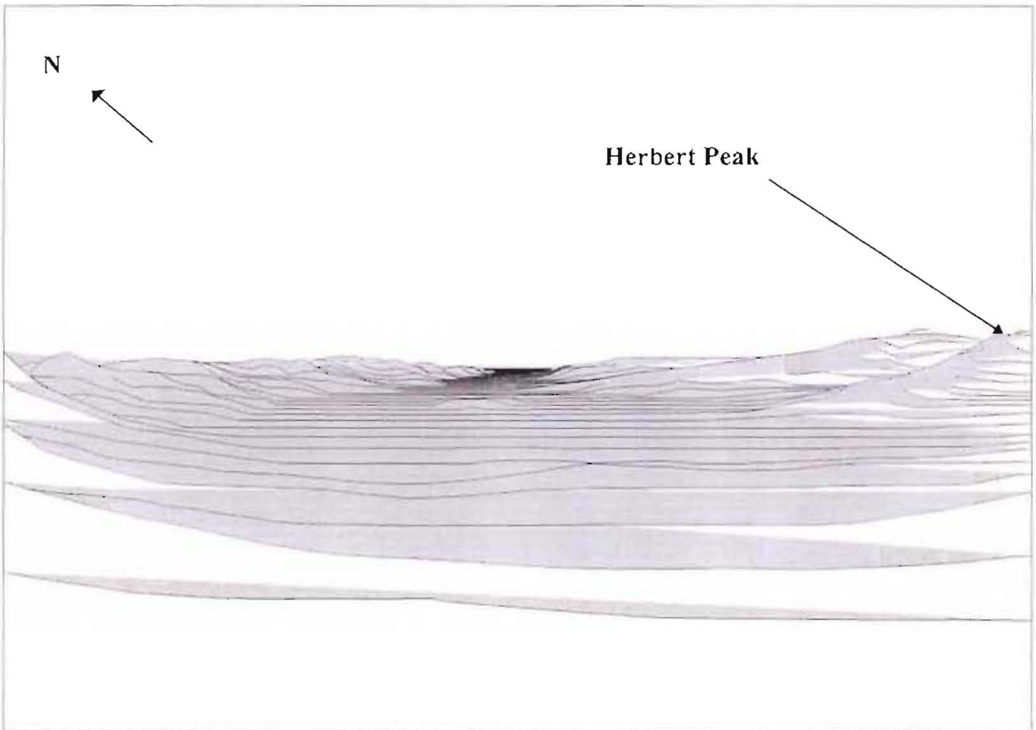


Figure 4.2c. View from Gebbies Pass looking to the NE, generated by WAsP.

Figure 4.2d. View from the road going south through the Gebbies Pass.

4.3.2.2 Mount Herbert (917m a.m.s.l.)

This hill stands well above the surrounding terrain and is the highest point on Banks Peninsula. This is quite an expansive tussock-covered area with gently rounded summit slopes which are unlikely to cause flow separation in any direction near the summit. The anemometer is mounted on a 12m metal lattice mast at the top of Herbert Peak at a height of 10m a.g.l. See Figure 4.3.

Figure 4.3a. View of the Banks Peninsula for Sugar Loaf (Mt. Herbert is to the right, out of the picture).

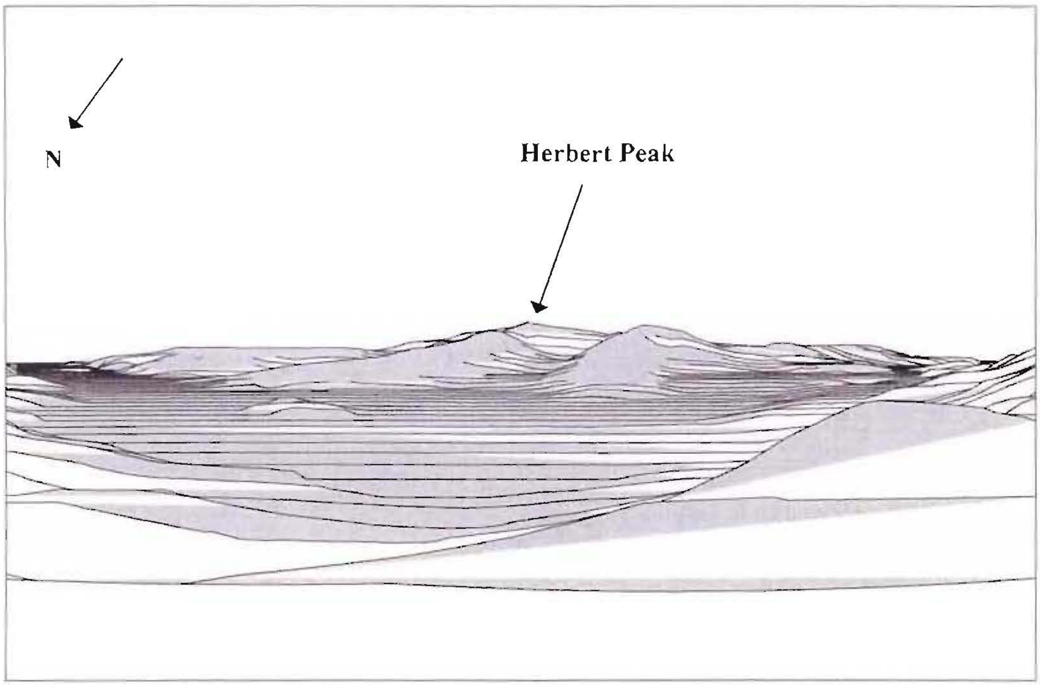


Figure 4.3b. Computer generated view of Mt. Herbert from Sugar Loaf.

4.3.2.3 Sugar Loaf (496m a.m.s.l.)

The steep dome-shaped summit is surrounded by steep bluffs on the SE side facing the harbour and more gentle on the NW side. Wind data from this site were collected by two anemometers mounted to a Television New Zealand (TVNZ) transmission tower at 24 m and at 122m above local ground level for a longer period of time than other sites. Some shelter at low level is expected from the E-SE winds which dominated much of the 1981 survey period. See Figure 4.4.

Figure 4.4. Sugar Loaf site with TVNZ tower (top anemometer is 122m a.g.l.).

4.3.2.4 Marley's Hill (502m a.m.s.l.)

This is a rounded peak and does not have the steep slopes to the harbour like its neighbour Sugar Loaf. It is expected that the wind direction at the summit would be influenced by channeling through the harbour which lies on a NE-SW axis. The anemometer was mounted at the summit on the top of a 30m VHF antenna. There is a stand of 20m high trees to the north of the site which is likely to provide shelter from the NW direction. Figure 4.5 shows a view of the Marley's hill summit, looking to the NW; the 30m VHF antenna is the one on the left of the photo.

Figure 4.5. View of the Marley's hill summit, looking to the NW.

Figure 4.6. View of Marley's Hill and Sugar Loaf from Gebbies Pass.

4.3.2.5 Godley Head (245m a.m.s.l.)

This site is well exposed to winds from all directions, in particular to the coastal NE winds that often blow as a strong sea breeze during the summer months. Although the ridge line is relatively flat in cross-section, steep slopes and high bluffs line the water's edge on both sides. The anemometer was mounted on a 10m pole on the exposed grassy ridge which extends NE out to the sea at the northern end of the Port Hills ridge line. See Figure 4.7.

Figure 4.7. Godley Head seen from the south.

4.3.3 Regional Wind Climate[1]

This area is situated between latitudes 42°30'S and 45°S and lies between the southern hemisphere anticyclone belt and the sub-polar depression zone. Weather systems progress generally from west to east in a sometimes regular and sometimes irregular manner. One regular pattern has an anticyclone coming onto central New Zealand giving regional light winds and clearish skies to Canterbury. In winter this results in light surface northwesterly drainage winds down the plains and in summer, coastal sea breezes. On the western side of the anticyclone, west to northwesterly winds flow over the central and southern parts of the country. The maritime surface northerly winds through Cook Strait follow the coast southwards to the lee of the Kaikoura Ranges and are brought inland over the northern plains by Banks Peninsula. This can be reinforced by sea breeze activity, especially in summer. This coastal north to northeasterly airstream flows with moderate intensity up Lyttleton Harbour and accelerates through the Gebbies Pass saddle. It also accelerates as it ascends the

[1] Extracted from Cherry and Smyth [30].

northern slopes of Banks Peninsula, giving regular moderate to strong winds over the peninsula.

The northwesterlies following around the rear of the anticyclone are often moderate to strong and sometimes gale force through much of the depth of the troposphere. The mountains provide a good deal of shelter in the lower layers of the air but on regular occasions there are severe down-slope winds to the lee of the mountains with a train of lee waves being formed. Surface wind speeds are especially strong under the first lee wave (the primary wave) giving gale force winds in the area to the lee of the front ranges. Elevated sites on Banks Peninsula such as Mount Herbert record very high winds during these conditions and so it is probable that the rounded hills and summits experience high winds during the northwesterlies.

The departure of the anticyclone is usually followed by the arrival of a maritime sub-polar south to southwesterly airstream whose front travels onto the country with a band of high winds ahead of it. The air mass behind the front is generally less windy than the prefrontal northwesterly, but it usually brings moderate to strong winds initially, decreasing slowly as the pressure gradient weakens with the approach of the next anticyclone. The wind across the Canterbury plains remain at moderate to high levels for some time in southerly conditions.

Irregular patterns are also common. Two occurrences are frequently experienced. The first is a succession of cold fronts bringing persistent south to southwesterly weather, with light to strong winds in the region of the fronts. The second regular deviation occurs when a depression forms in the Tasman Sea. These can be slow moving and result in an extensive area of cloud and rain extending across the country with winds from the easterly quarter flowing onto the South Island bringing persistent heavy rain to the eastern side of the mountains.

From above discussion the main dominant wind regimes for the Port Hills may be divided into three categories:

- E/NE winds produced by the low-level coastal N/NE airstream from Cook Strait and the coastal sea breezes.
- The S/SW winds are the next most prevailing surface winds followed by the 'calms'.
- The W/NW winds have low frequency at the surface level while they are very frequent above the boundary layer.
- Winds from the SE are very infrequent at the surface level.

The topography is a major factor in the local wind regime, and in the case of Canterbury it is a determining factor for the regional wind climate since the Southern Alps interact very strongly with the prevailing westerly winds. This study investigates effects of local topography on the prevailing wind regimes and looks at different practical methods to predict changes in wind behaviour.

4.4 LOW LAND AND ELEVATED SITE WIND CHARACTERISTICS

4.4.1 Thermal effects

WECS obtain their energy from winds flowing near the surface of the ground derived from the synoptics scale processes associated with the weather systems. Massive movements of air occur to redistribute the absorbed solar energy. The earth's surface being rough slows the air in contact with it and forms a surface boundary layer. Through this layer the mean wind speed increases with height. The energy is supplied at the top of the boundary layer. Its transport downwards is a function of the mechanical and thermally induced turbulence. This is controlled by the thermal instability of the layer of air in the boundary layer. Surface heating, as occurs with the diurnal and seasonal solar cycles, decreases the stability of the air near surface. This decreases the wind speed in the upper layers of the boundary layer and increases the wind speed near the surface.

4.4.2 Elevated wind regimes

A site like Mount Herbert with an elevated wind regime has a high mean wind speed, in excess of 8 m/s at 10 m a.g.l., a small diurnal range of wind speed with the maximum occurring overnight and the minimum occurring during the afternoon. The mean wind speeds are higher in winter than summer (Cherry and Smyth [30]).

4.4.3 Lowland wind regimes

Gebbies Pass, Sugar Loaf, Marley's Hill and Godley Head exhibit lowland wind regime characteristics. They are characterised by a large range in the diurnal mean wind speed with the maximum occurring during the afternoon and the minimum occurring in the morning. The Gebbies Pass seasonal trend is for maximum monthly mean wind speeds to occur in summer and minimum wind speeds to occur in winter. This trend is reversed for Sugar Loaf, Marley's Hill, and Herbert Peak. Figure 4.8 shows monthly mean wind speeds for lowland and elevated sites around Banks Peninsula.

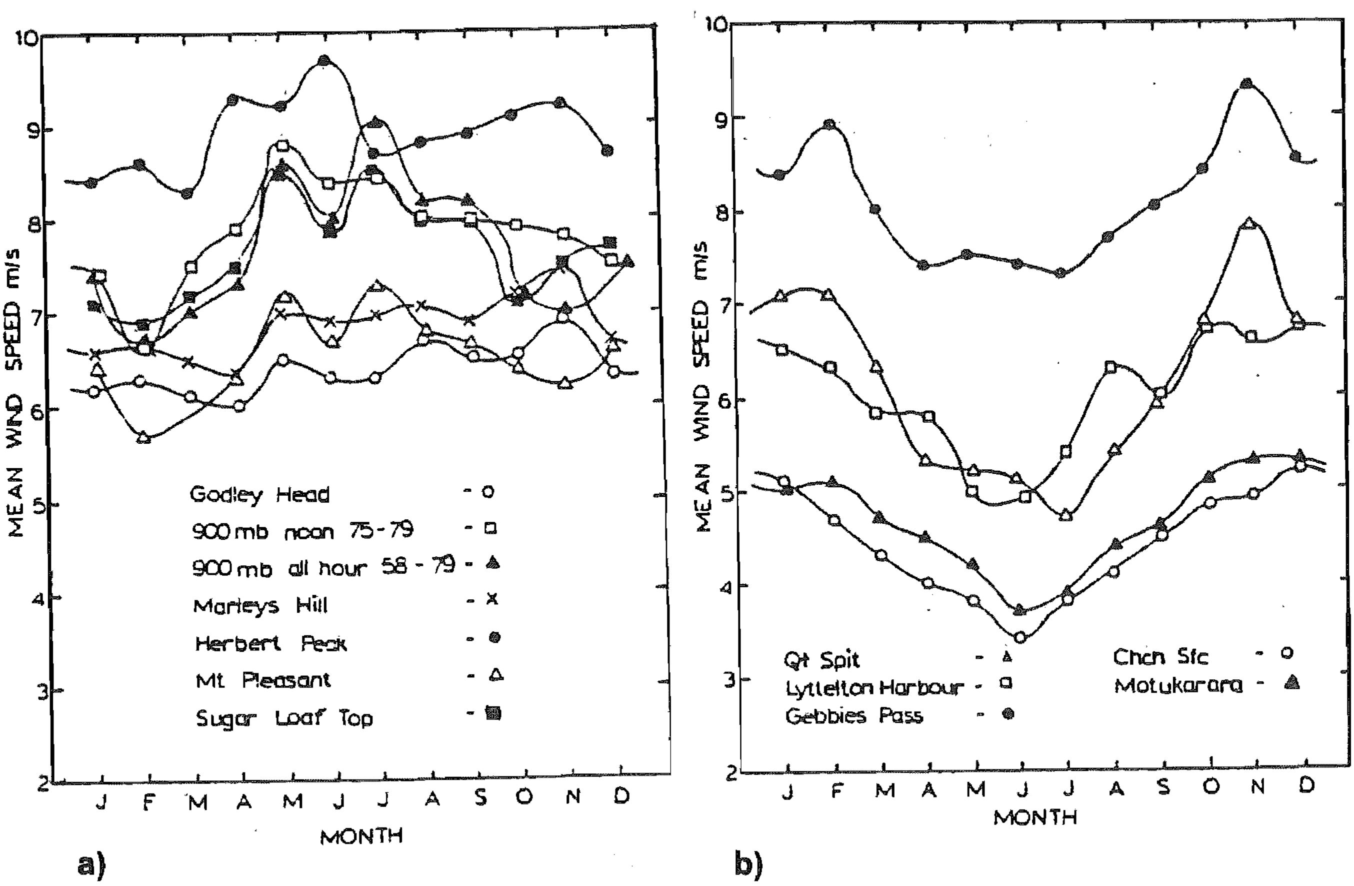


Figure 4.8. Monthly mean wind speeds for a) lowland and b) elevated sites around Banks Peninsula.

4.5 WAsP APPLICATION TO THE PORT HILLS REGION

4.5.1 Wind information from reference sites

4.5.1.1 Christchurch Airport (30m a.m.s.l.) - Jan 1960 to Dec 1978

Christchurch Airport is situated on the open, flat Canterbury plains about 9km west of the city of Christchurch and 15km NW of the Port Hills. The cup-generator anemometer is on a 14m mast near the runway intersection at about 550m from the terminal building with no nearby obstructions. The prevailing wind is from the NE produced by the low-level coastal N/NE airstream from Cook Strait which includes a significant coastal sea breeze component. SW winds are often associated with the passage of cold fronts and the NW winds bring warm, dry gusty winds which on occasions, result in extensive damage to property, Cherry [35]. The terrain is very simple and the only slight local enhancement is caused by the prevailing northeasterly and southwesterly being forced to flow around the western side of Bank Peninsula Hills.

Regular readings of hourly mean wind speed and direction have been recorded at this site since 1960. A reference data record for the Christchurch Airport was already available in the form of a meteorological table for the period of 1960 to 1978. The format of this table was modified so it could be processed by WAsP, see Appendix A2. This data excludes 'calm winds' - less than 2 knots (~1 m/s). Calm intervals form 14% of total wind observations during this period. However, the average mean wind speed obtained by WAsP from this data is 4.5m/s and agrees closely with the accepted value of 4.4 m/s (including calms) for this site. Figures 4.9a, b show the sector-wise frequency distribution of the wind generated by the WAsP. These figures were created by taking camera shots of the screen (using a digitised camera). This is why the quality of the graphics is poor.

Smyth [36] suggests a roughness length of 0.2m for this site from his Power-Law Profile Index. Using this value, WAsP overestimates wind speeds for the Port Hills sites in order of 100 - 200% of the measured values. Consulting with the typical terrain roughness chart (WAsP User's Guide, page 22 [21]), the roughness length for the site was estimated to be 3cm - roughness class 1. This value proved to represent the surface characteristics better and give more realistic predictions. WAsP recognition of terrain features is through the use of obstacles and the actual terrain roughness. Terrain roughness only covers physical terrain texture. Other wind obstructing features (e.g. buildings and shelter belts higher than 1/3 and closer than 50 of the anemometer height) are modelled as an 'obstacle'.

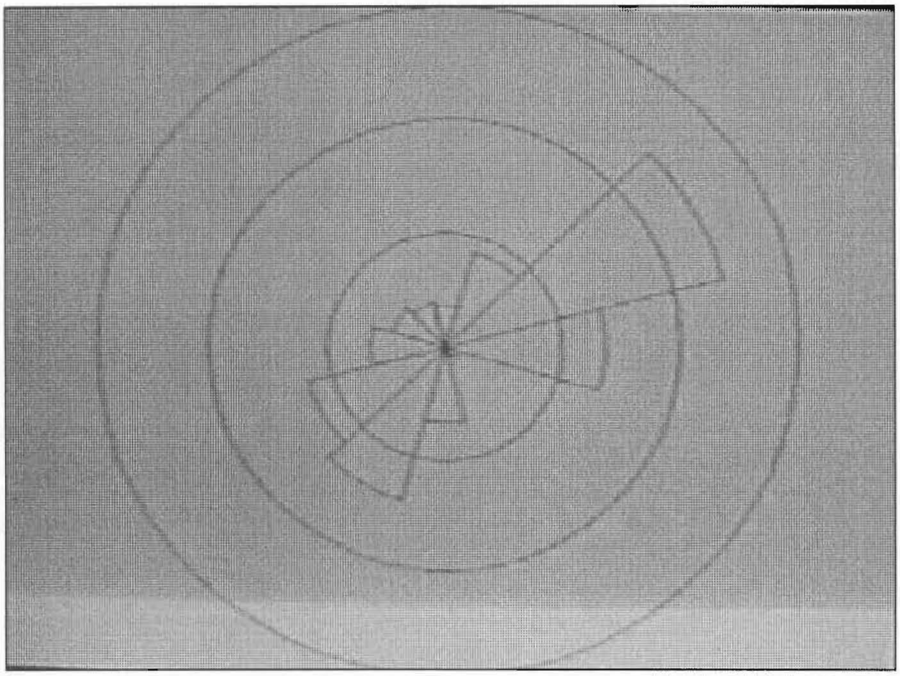


Figure 4.9a. Sector-wise frequency distribution of the wind in the form of a wind rose for Christchurch airport (Jan 1960 to Dec 1978) .

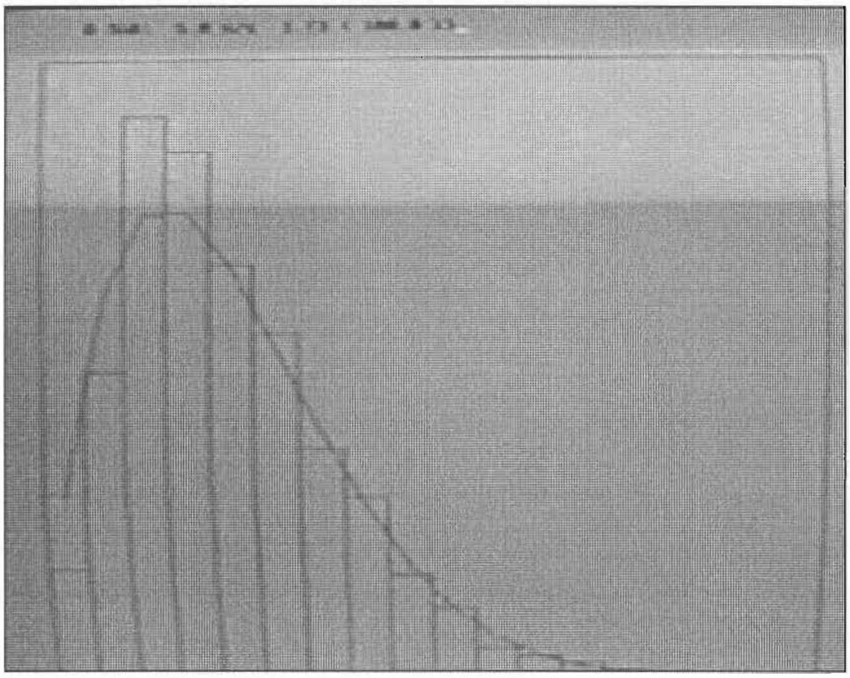


Figure 4.9b. Sector-wise frequency distribution of the wind with the Weibull distribution fitted to the data, 0-360° (Jan 1960 to Dec 1978).

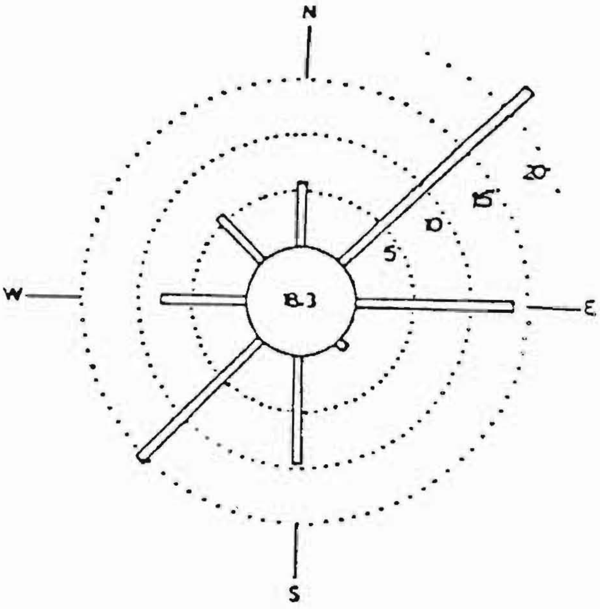


Figure 4.9c. Wind direction rose taken from the field data (Jan 1960 to Dec 1978).

4.5.1.2 Christchurch Airport (30 a.m.s.l.) - Jun 1981 to Nov 1981

An alternative reference record for Christchurch Airport was purchased from the National Institute of Water and Atmospheric Research (NIWA) based on the hourly mean wind speed and direction. Calm intervals (calm threshold is 1m/s) form 23% of this record for the 6 month period from June to November 1981. This data period coincides with that of the field data from Smyth [34] for the sites of interest. The average mean wind speed of this data record, calculated by WAsP, is 4.4 m/s, which is very close to the field mean wind speed of 4.23 m/s obtained by Smyth [34]. Figures 4.10a, b display the wind frequency occurrences for this period.

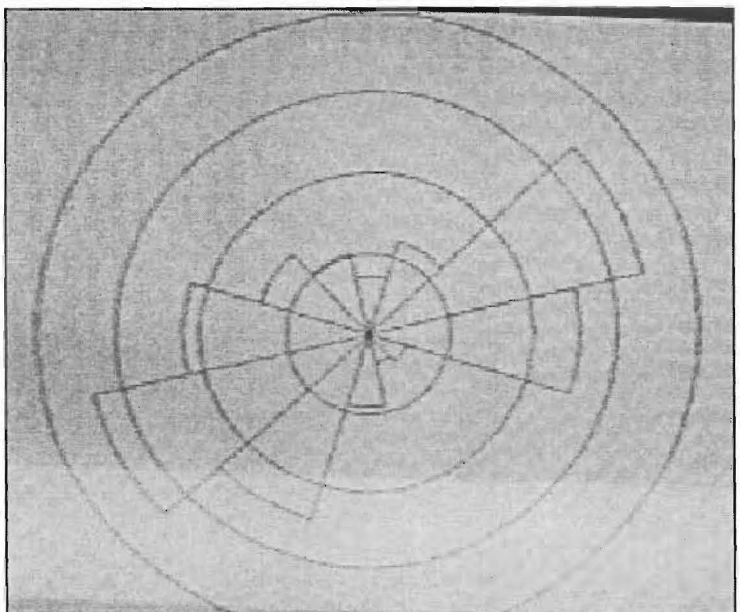


Figure 4.10a. Sector-wise frequency distribution of the wind in the form of a wind rose (from Jun 1981 to Dec 1981).

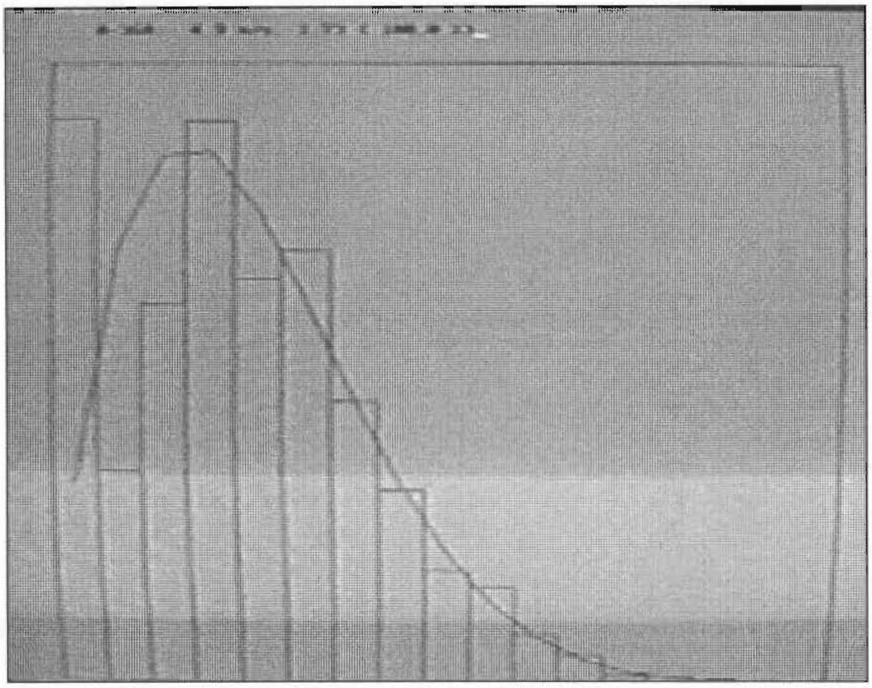


Figure 4.10b. The sector-wise frequency distribution of the wind with the Weibull distribution fitted to the data, 0-360° (Jun 1981 to Nov 1981).

4.5.1.3 Lincoln climate station (11m a.m.s.l.) - May 1975 to April 1978

Additional reference wind data were obtained from the Lincoln site located on the western side of the Lincoln University campus, some 20km south of Christchurch. This site has a well documented wind speed history extending back to the 1880's. Since then it has been subjected to several site changes due to change in local environment, the latest of which was in January 1976. The terrain in this site is flat, open farm land with spaced trees and shelter belts with an expected roughness length between 0.1 and 0.3 m, Cherry and Smyth, [30]. Some local shelter from the southerly winds is anticipated at this site due to the adjacent 5m high shelter belt, south of the anemometer. These were modeled as obstacles and entered into the WAsP obstacle menu. The roughness length for the site itself was taken to be 3cm.

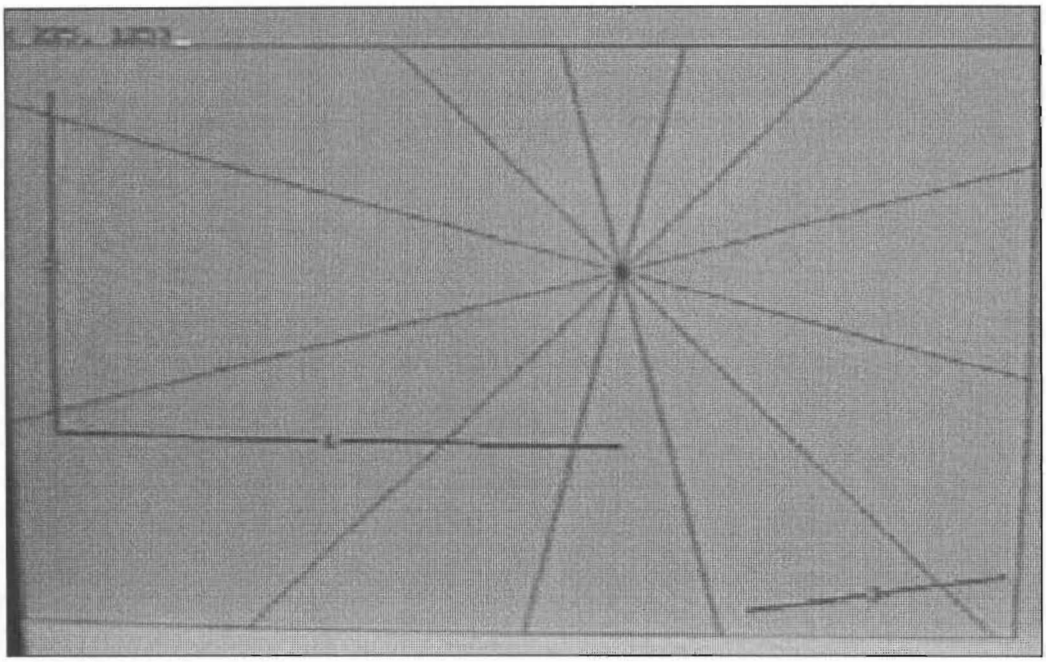


Figure 4.11. Obstacle file for Lincoln College site. Lines 1, 2, and 3 are obstacles around the site

This data record also excludes calm periods. N to NE winds dominate the site. Figures 4.12a, b show same wind information for the Lincoln site as in Figures 4.9 and 4.10.

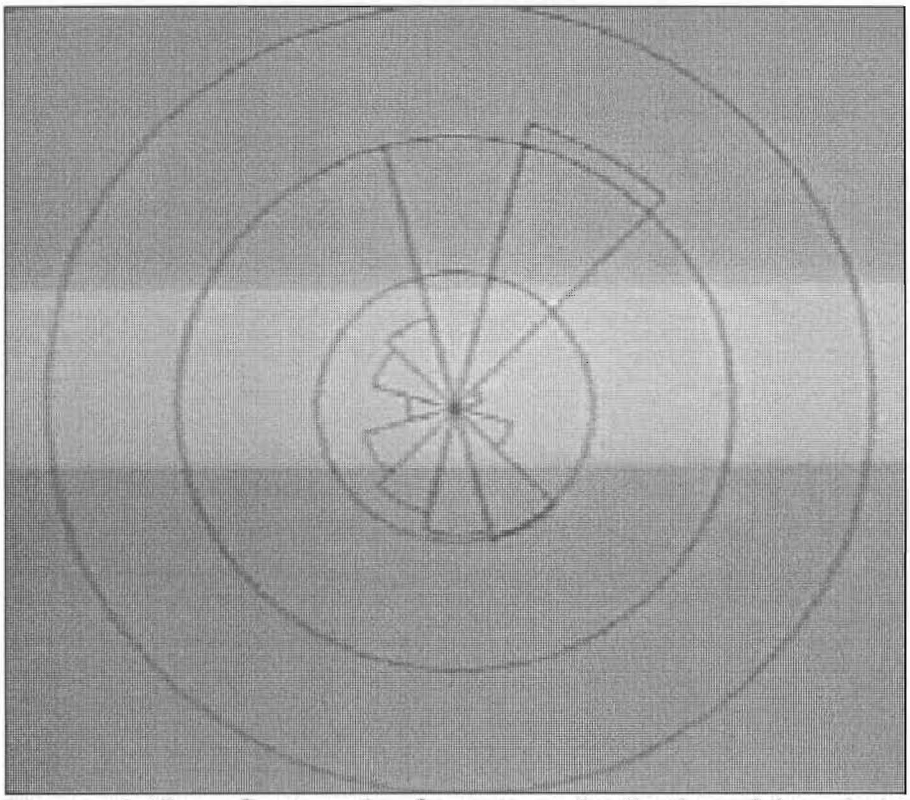


Figure 4.12a. Sector-wise frequency distribution of the wind in the form of a wind rose for the Lincoln site.

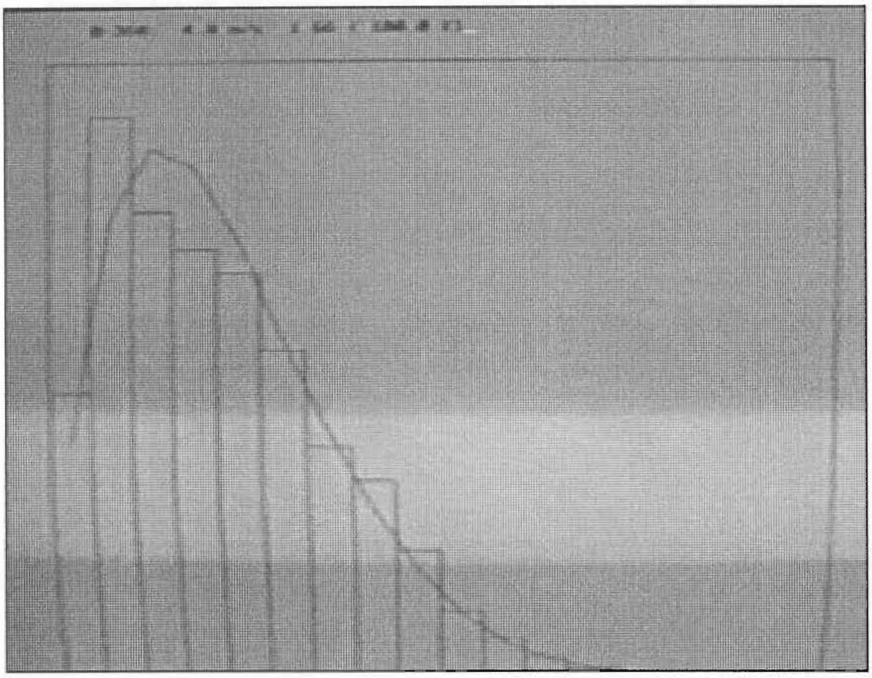


Figure 4.12b. Sector-wise frequency distribution of the wind with the Weibull distribution fitted to the data, (0-360°).

4.6 TOPOGRAPHICAL INPUT TO WAsP

4.6.1 Digitised map of the Port Hills

A pre-digitised height contour map of the area was first obtained from the Geography Department of the University of Canterbury. This map contained information for the Port Hills region and the Banks Peninsula with height contours spaced in 5m intervals. At first, the format of this map file had to be changed to make it compatible with the WAsP specified format. However, this file proved to be too large for the WAsP program to load since it contained far in excess of 16,000 data points, a limit set by the WAsP orographic model. In fact, it contained in excess of 190,000 coordinates. Another computer program was developed to perform several simultaneous operations on the existing map file to:

- break the file into smaller files containing selected height contours,
- select contours close to the peaks to have the maximum required number of data points and,
- delete insignificant coordinates in low elevation contour lines away from the sites, without jeopardising the accuracy of the map.

This operation created nineteen smaller files. Each individual file was loaded into WAsP and it was further trimmed using the internal trimming facilities provided in Orographic menu. All these files were then patched together as they were reloaded onto WAsP. The final map contained just under 16,000 data points with a contours resolution of:

- 10m in close proximity to the hill sites;
- 20m and 50m progressively further away from the sites and;
- 100m in the low land elevation areas.

Figure 4.13 shows the resulting simplified contour map of the Port Hills area together with the points of interest and their elevations (Godley Head, Sugar Loaf, Marley's Hill, Gebbies Pass and Mt. Herbert).

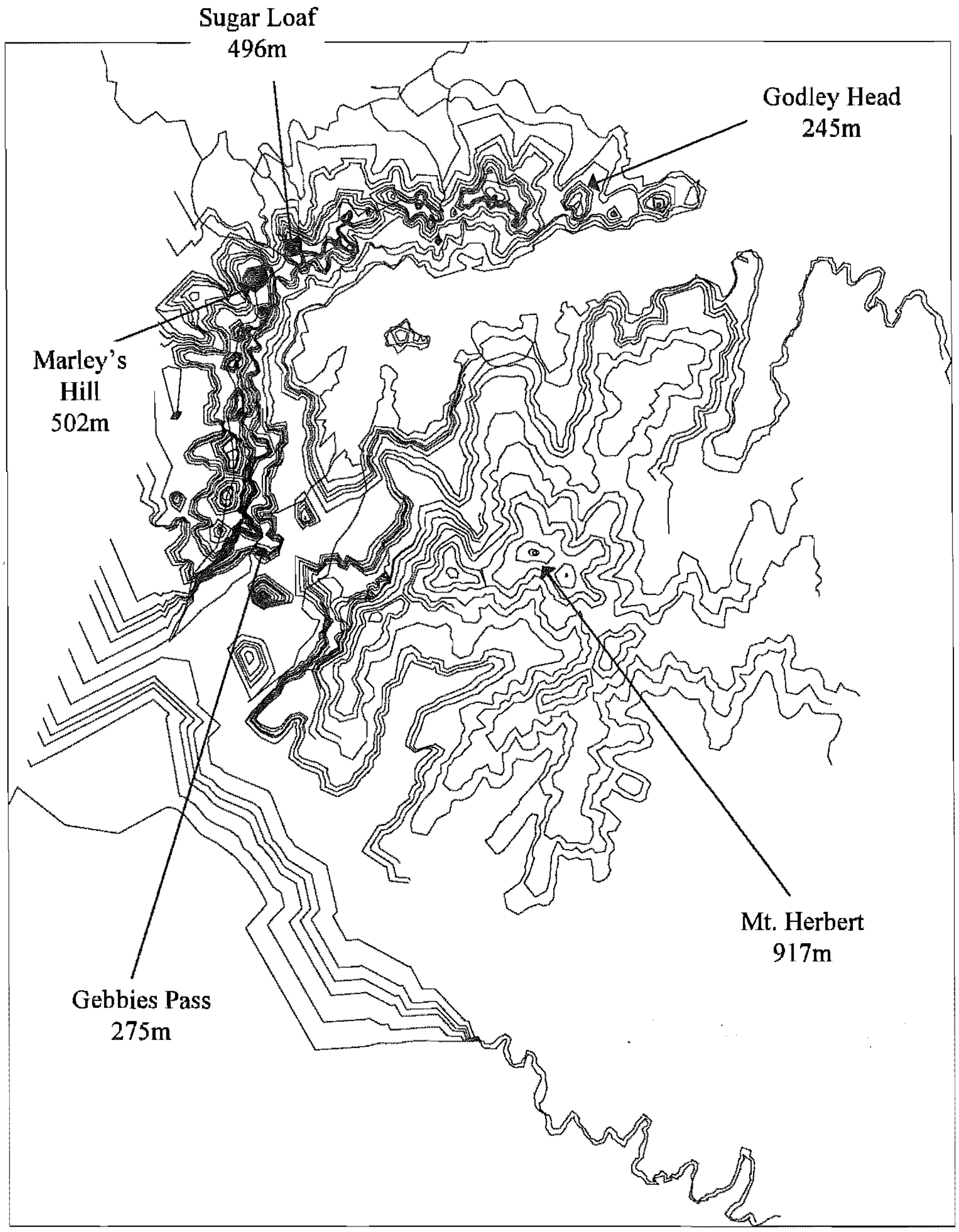


Figure 4.13. Computer generated contour map of the Port Hills area.

This stage of the research was found to be considerably time consuming. Each individual maps had to be carefully studied to make sure it represented the terrain features as accurately as possible. Although WAsP is able to process and analyse these individual maps separately, the effects of surrounding terrain on a particular site can be lost. Hence, one single map was compiled to include all the selected sites.

4.7 OBSTACLES

From a visit to Christchurch Airport it was found that the meteorological mast is not sheltered by any significant obstacles. The nearest terminal building is about 550m away from the site. The same was found from a trip to the Port Hills area. All the sites are located on the exposed terrain. Therefore, WAsP models the Port Hills sites without any obstacles; i.e. the Obstacle model was cleared for each WAsP execution. There is a shadow effect of the lattice tower at the Sugar Loaf site which is discussed later.

There are some sheltering effects on Lincoln College by surrounding shelter belts. They are modeled as obstacles for this site. See Figure 4.11.

4.8 ROUGHNESS

A roughness map of the Port Hills area was prepared using an external digitiser since the internal digitising facility of WAsP could not be installed. The digitiser belonged to the Civil Engineering Dept. of Canterbury University. Some initial work had to be done to change the output string of the digitiser from binary to ASCII codes. The digitising operation was very time consuming since each roughness line had to be digitised and stored separately. Then they were all patched together into a roughness map file coherent to WAsP specification. Roughness values assigned to each line were derived by consulting:

- typical terrain roughness charts (WAsP User's Guide page 22);
- results of previous wind tunnel study of the area;
- with the research leader (Dr A.J. Bowen) who has a vast amount of practical knowledge about this area.

Figure 4.14 shows the roughness map of the Port Hills area produced by WAsP.

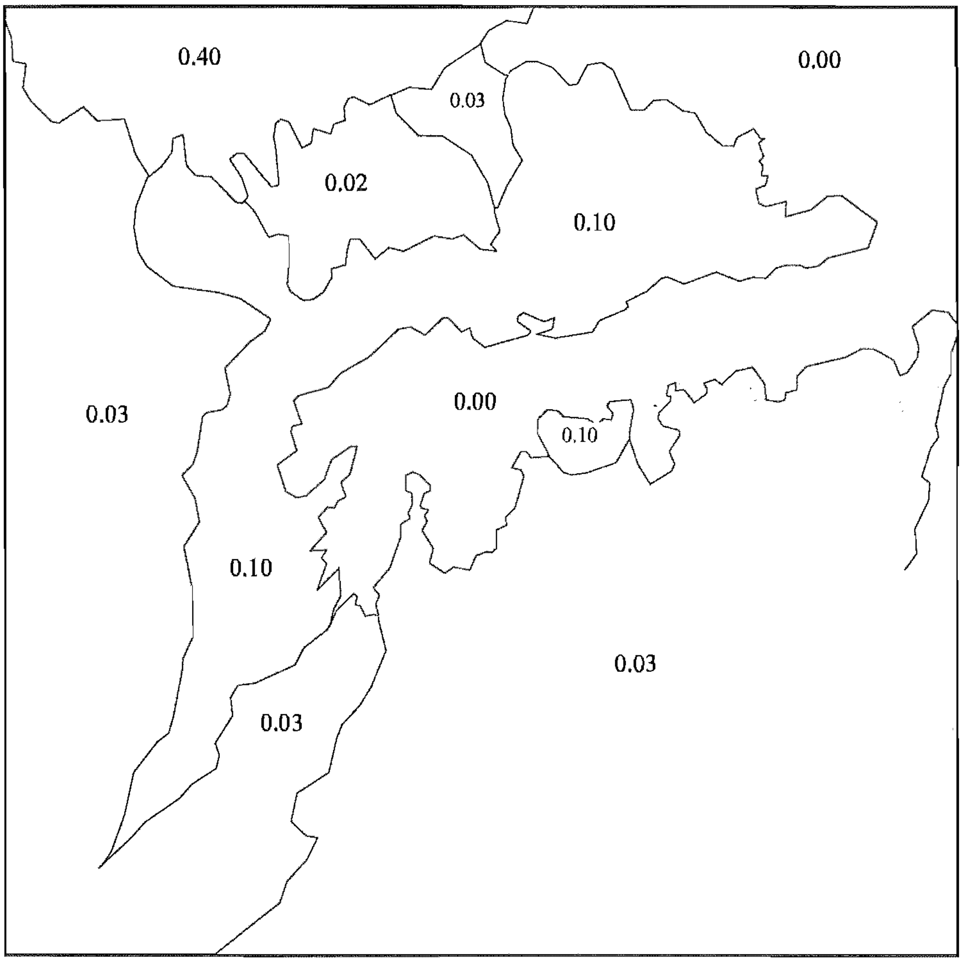


Figure 4.14. The roughness map of the Port Hills area produced by WAsP. The numerical values inside each boundary represent the roughness length Z_0 (in meters) for that area.

4.9 APPLICATION OF WAsP TO THE PORT HILLS REGION

Using the wind data and topographical information described above, the WAsP program was run to generate a wind atlas data set for Christchurch Airport. A preliminary WAsP prediction of mean wind speeds for the selected sites on the Port Hills are presented and compared with the field measured data in Table 4.1.

Table 4.1. Mean wind speeds for all directions from field measurements and WAsP predictions. Values inside brackets represent percentage of over-estimation by WAsP.
Reference wind data: Christchurch Airport, 1960 to 1978 (data excludes calm periods).

	Elevation a.m.s.l. (m)	Anemometer Height (m)	Field mean wind speed (m/s)	WAsP mean wind speed (m/s)
Christchurch Airport	30	14	4.4	4.5 (2%)
Lincoln College	11	10	4.4	4.2 (-4%)
Gebbies Pass	275	10	8.1	7.8 (-4%)
Mount Herbert	917	10	8.9	11.5 (29%)
Sugar Loaf	496	24 122	6.2 7.7	9.7 (57%) 9.8 (27%)
Godley Head	245	10	6.4	10.1 (58%)
Marley's Hill	502	30	7.1	8.9 (25%)

It is apparent that WAsP has overestimated mean wind speeds except for the Gebbies Pass site. This over-estimation is more severe for Sugar Loaf (24m) and Godley Head. Further time was spent to investigate the reasons behind this disagreement. This lead to two major adjustments to the input data into WAsP, namely:

- selection of wind reference data such that its recording period would coincide with that of site measurements, and includes calm intervals.
- inclusion of orographic information for the reference site in the area map.

The first adjustment was easily achieved. A wind data record for Christchurch Airport was purchased from the National Institute of Water and Atmospheric Research (NIWA). The recorded period is the same as the period of field measurements by V Smyth; i.e. June 1981 to November 1981.

The second improvement proved to be slightly laborious. The original digitised map did not contain any height contours for Christchurch Airport. The WAsP program supports the international mapping coordinate system and it was able to locate the position of the reference site (i.e. Christchurch Airport) relative to the location of other sites on the Port Hills. It calculated a height of 32m a.m.s.l. (the actual height is 30m a.m.s.l.) for Christchurch Airport which was quite satisfactory. A wind atlas data set based on this height produced the above predictions. After further investigations, it was realised that WAsP calculated the height of the reference site by looking at the nearest available contour line in the map file and, hence, creating a fictitious wind atlas data set for this site. It was by coincidence that the nearest height contour had a height of 32m a.m.s.l.

Because the WAsP digitising facility could not be installed and Christchurch Airport terrain is fairly simple, a simple but effective method was devised. The terrain for

Christchurch Airport was modeled by a simple Gaussian (bell-shaped) hill. This hill has the following characteristics:

- height of 30m a.m.s.l.;
- center of hill location is 2473610,5747290 m;
- half-widths of 2000m for both major and rninor axis.

Lincoln College is also not represented in the prepared map file, so the exercise was repeated for this site:

- Height of 11m a.m.s.l.;
- center of hill location is 2467000,572800m;
- half-widths of 2000m for both major and minor axis.

By choosing a very large value for the half-width (2km), the effect of speed-up factor at the reference sites is minimised and can be neglected. The final maps are shown in Figures 4.15a and 4.15b.

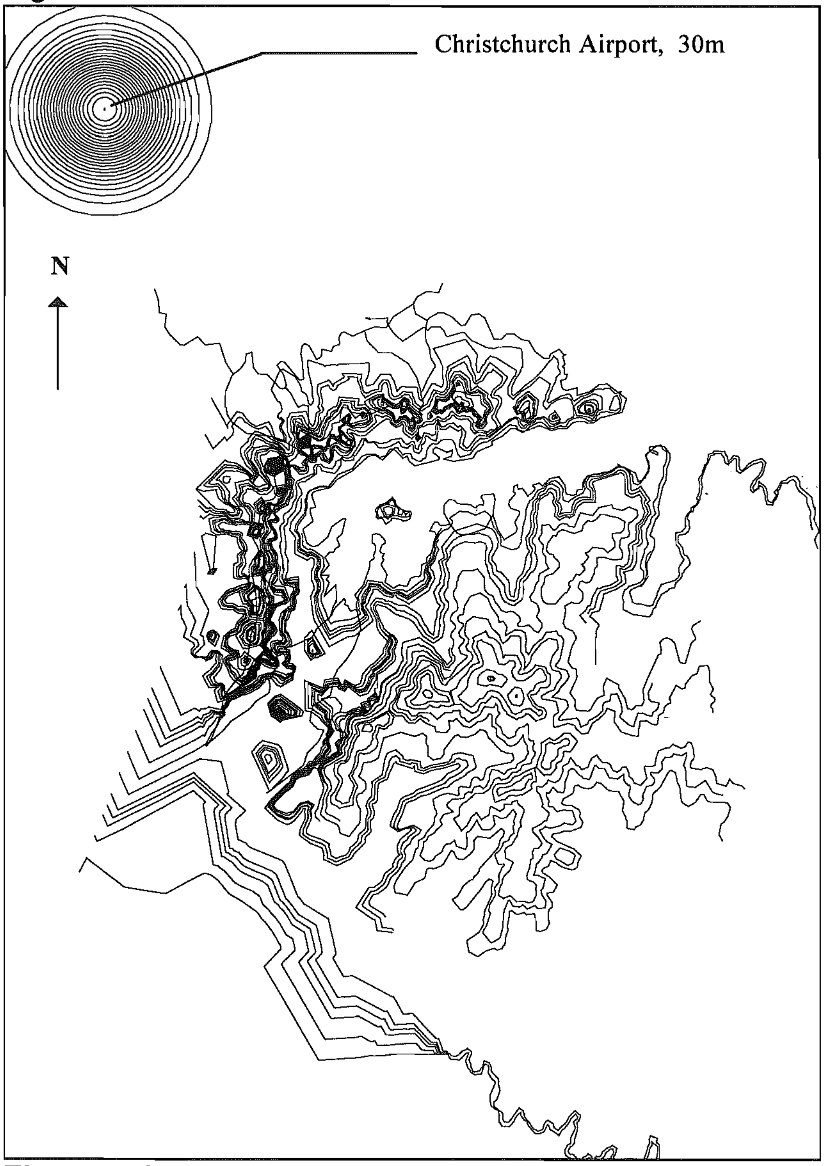


Figure 4.15a. Computer generated contour map of the Port Hills area including Christchurch Airport.

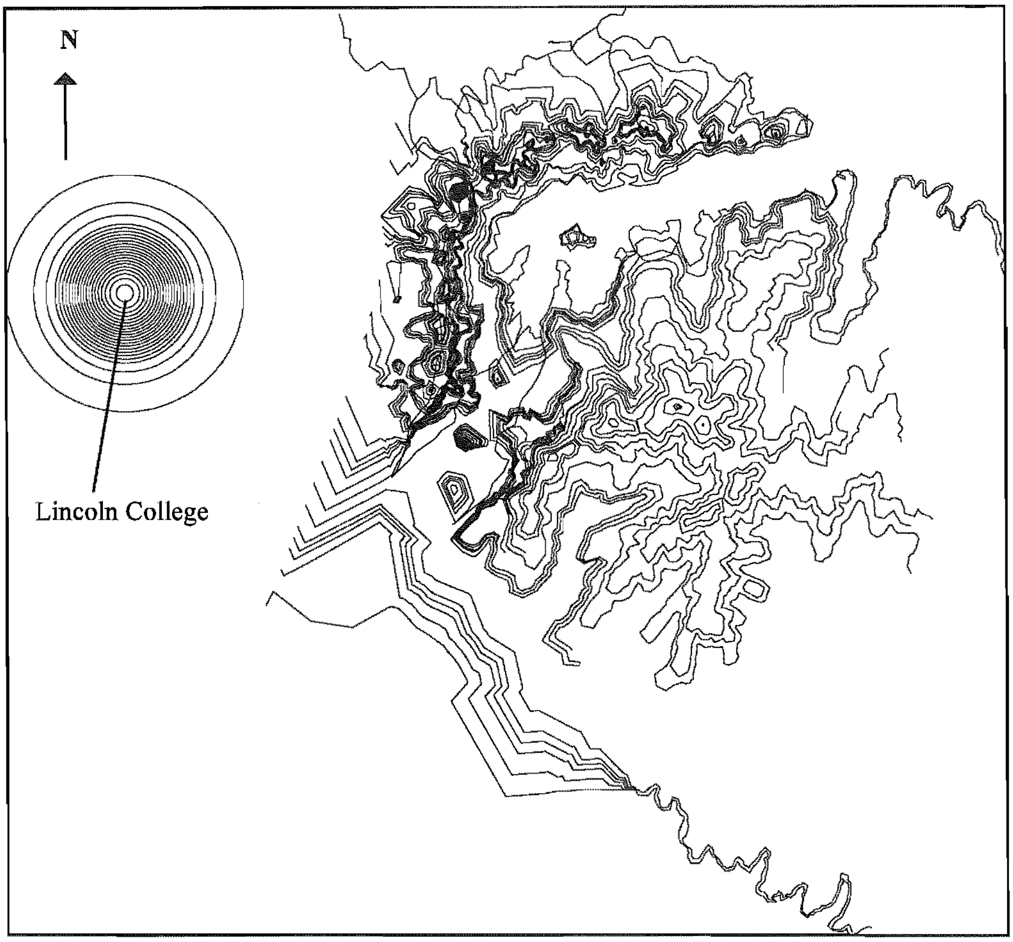


Figure 4.15b. Computer generated contour map of the Port Hills area including Lincoln site.

Before proceeding to re-calculation of wind speed for the selected sites, it was decided to generate, initially, wind atlas data sets for two reference sites (i.e. Christchurch Airport and Lincoln College). Each station is used to predict wind climate at the other station. Results are presented in Table 4.2 in a score scheme (Troen and Petersen [3]). The first column contains the predicted stations and the first row the predictor stations. The actual measured values are shown in the last column.

Table 4.2. Measured and estimated wind speeds for two reference sites at anemometer heights.
Reference wind data: Christchurch Airport: 1960 - 1978; Lincoln College: 1975 to 1978. (Data exclude calm periods).

	Christchurch Airport (m/s)	**Lincoln College (m/s)**	***Measured data (m/s)***
Christchurch Airport	4.5	4.8	*4.4*
Lincoln College	4.3	4.3	*4.4*

Figures 4.16 and 4.17 display sector-wise frequency of wind occurrence for each site, calculated both from its own and the other reference station wind data.

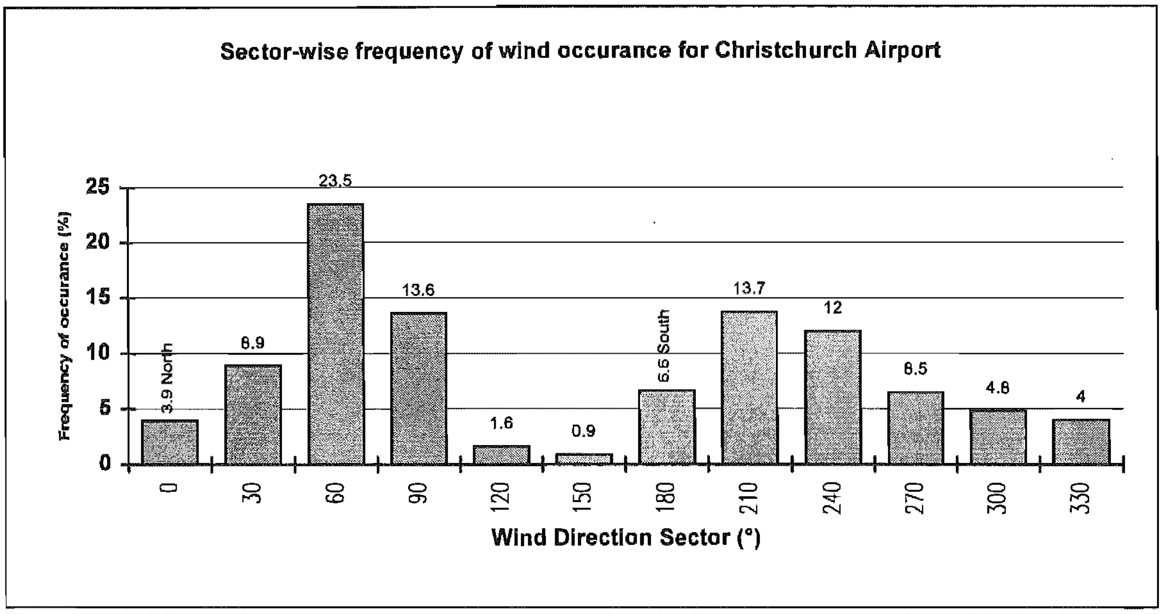


Figure 4.16a. Sector-wise frequency of wind occurrence for Christchurch Airport calculated by WAsP from measured Christchurch Airport wind data.

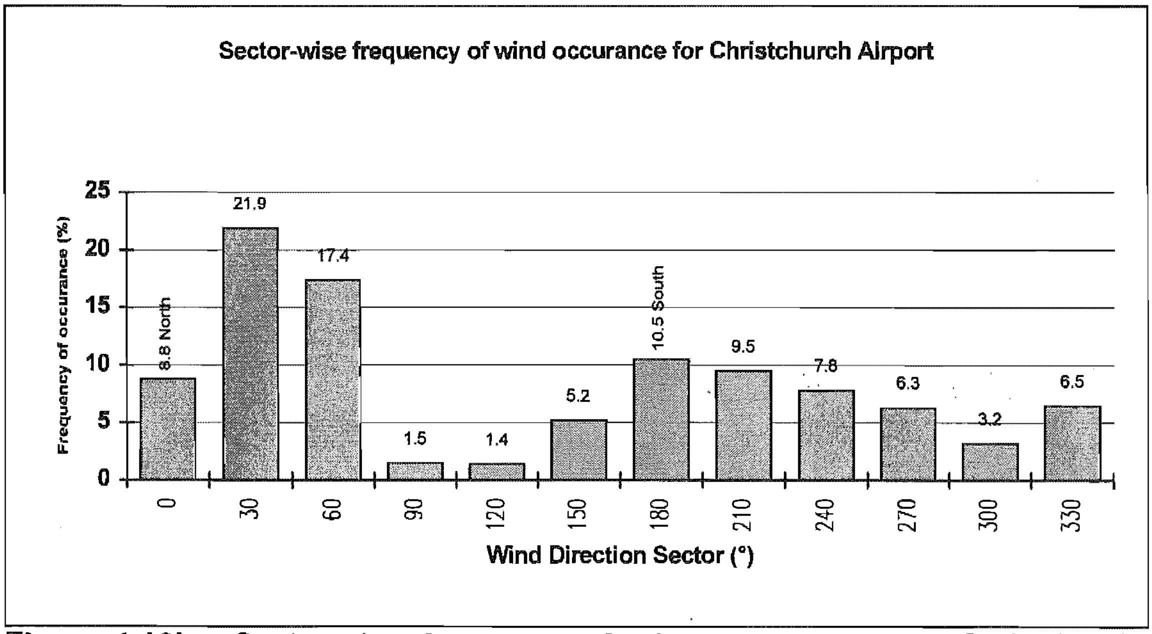


Figure 4.16b. Sector-wise frequency of wind occurrence for Christchurch Airport calculated from Lincoln station wind data.

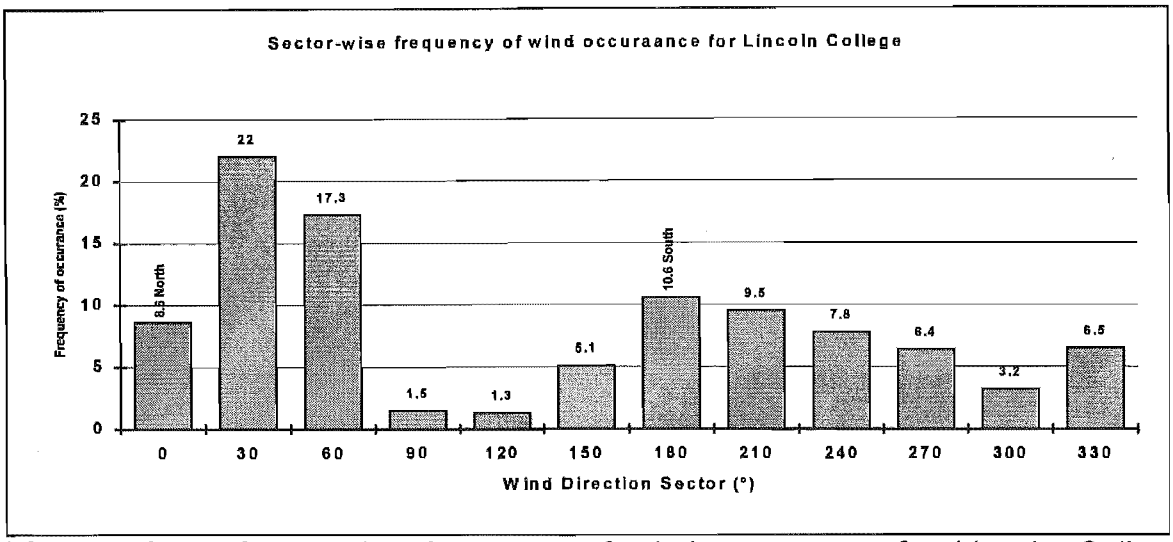


Figure 4.17a. Sector-wise frequency of wind occurrence for Lincoln College site calculated by WAsP from recorded Lincoln station wind data.

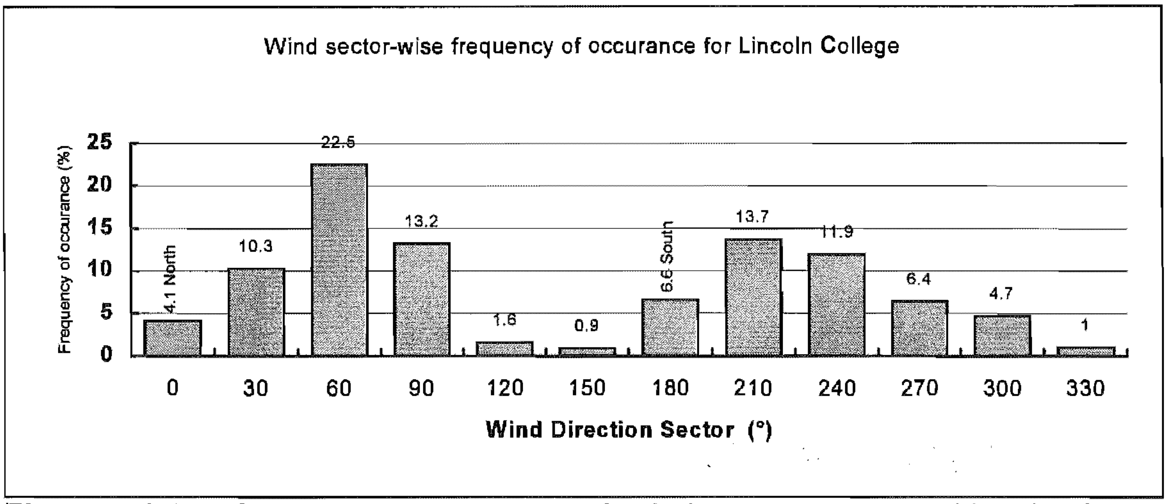


Figure 4.17b. Sector-wise frequency of wind occurrence for Lincoln College site calculated by WAsP from Christchurch Airport wind data.

It is apparent from Table 4.2 that WAsP has predicted the wind climate at both reference sites very closely to the measured data, using the revised map. The accuracy is slightly higher for the self-predicted sites. Terrain at both sites are simple and homogeneous. Hence, each site predicts the wind climate of the other as being identical to its own wind frequency distribution. Compare Figures 4.16a with 4.17b and 17a with 16b. The close agreement is due to the fact that reference sites' terrain is extremely simple - a simple bell-shaped hill. Both sites have been assigned with similar roughness lengths. The Askervein Hill experience showed that WAsP was very good in predicting wind speeds at non-complex sites.

The sector-wise frequency of wind occurrence for each station has been plotted in Figures 4.16 and 4.17. The predicted wind distributions for each site, using the other station's wind data (Figures 4.16b and 4.17b), correspond very closely to the self-predicted data (Figures 4.16a and 4.17a). Since both sites are located on open land, the predicted wind distributions are almost identical to the predictor site wind climate. Compare Figure 4.16a with 4.17b and 4.17a with 4.16b. It is interesting to note that two sites' self-predicted wind distributions are out of phase by one sector - 30°. For Christchurch Airport, the maximum wind incidents occur in 60° and 90° (NE and E) directions, one sector ahead of Lincoln College site where its maximum wind occurrences fall in 30° and 60° (N and NE) directions, see Figure 4.17a and 4.16a. It is thought that the effects of shelter belts for Lincoln College site and its further in-land location have contributed to this phase difference in the wind distribution.

The average mean wind speed of 4.8 m/s, estimated by WAsP for the Christchurch Airport using Lincoln reference data, showed good agreement with the accepted value of 4.4 m/s (ex calms).

In general, WAsP close prediction of mean wind speed for the reference sites provides confidence to proceed further with the revised map. These two reference sites will be used to recalculate mean wind speeds at the selected sites on the Port Hills.

4.10 WAsP RE-CALCULATION OF MEAN WIND SPEEDS FOR THE SELECTED SITES

Using the revised map and the shorter term wind data acquired from NIWA, WAsP recalculated the mean wind speeds for the Port Hills sites. At this stage of the research, a correction in the software was advised by the WAsP program developing institute, Risϕ National Laboratory. It was suggested to set P_{34} parameter (True Up-wind direction in BZ Model in the *WAsP.par* file) to 1 to give better predictions in the complex terrain application. Tables 4.2a and 4.2b show WAsP predictions before and after the correction was made. Results are presented in Tables 4.3 to 4.5.

Table 4.2a. Mean wind speeds for all directions from field measurements and WAsP predictions - WAsP version 4.0. Values inside brackets represent percentage of over-estimation by WAsP.
Reference wind data: Christchurch Airport, June 1981 to November 1981 - data includes calm periods.

	Elevation a.m.s.l. (m)	Anemometer Height (m)	Field mean wind speed (m/s)	WAsP mean wind speed (m/s)
Christchurch Airport	30	14	4.23	4.4 (4%)
Lincoln College	11	10	4.4*	4.2 (-5%)
Gebbies Pass	275	10	7.87	7.3 (-9%)
Mount Herbert	917	10	9.12	9.3 (1%)
Sugar Loaf	496	24 122	6.0* 7.4*	9.1 (52%) 8.8 (19%)
Godley Head	245	10	6.59	8.8 (34%)
Marley's Hill	502	30	7.11	8.6 (21%)

Table 4.2b. As Table 4.2a but running WAsP version 4.1 (with correction - P_{34}=1).

	Elevation a.m.s.l. (m)	Anemometer Height (m)	Field mean wind speed (m/s)	WAsP mean wind speed (m/s)
Christchurch Airport	30	14	4.23	4.3 (1%)
Lincoln College	11	10	4.4*	4.2 (-5%)
Gebbies Pass	275	10	7.87	6.3 (-25%)
Mount Herbert	917	10	9.12	8.6 (-5%)
Sugar Loaf	496	24 122	6.0* 7.4*	8.8 (47%) 8.6 (16%)
Godley Head	245	10	6.59	8.6 (31%)
Marley's Hill	502	30	7.11	8.4 (18%)

* The field measurements during June to November 1981 do not include Lincoln College and Sugar Loaf sites. These values are for longer term, correlated at Christchurch Airport wind data by Cherry and Smyth [30].

Table 4.3. As Table 4.2a and running WAsP version 4.1 (with P_{34}=0)).

	Elevation a.m.s.l. (m)	Anemometer Height (m)	Field mean wind speed (m/s)	WAsP mean wind speed (m/s)
Christchurch Airport	30	14	4.23	4.4 (4%)
Lincoln College	11	10	4.4*	4.0 (-9%)
Gebbies Pass	275	10	7.87	7.1 (-10%)
Mount Herbert	917	10	9.12	9.1 (0%)
Sugar Loaf	496	24 122	6.0* 7.4*	9.1 (52%) 9.0 (22%)
Godley Head	245	10	6.59	8.3 (26%)
Marley's Hill	502	30	7.11	8.2 (15%)

* The field measurements during June to November 1981 do not include Lincoln College and Sugar Loaf sites. These values are correlated to long term wind speed at Christchurch Airport.

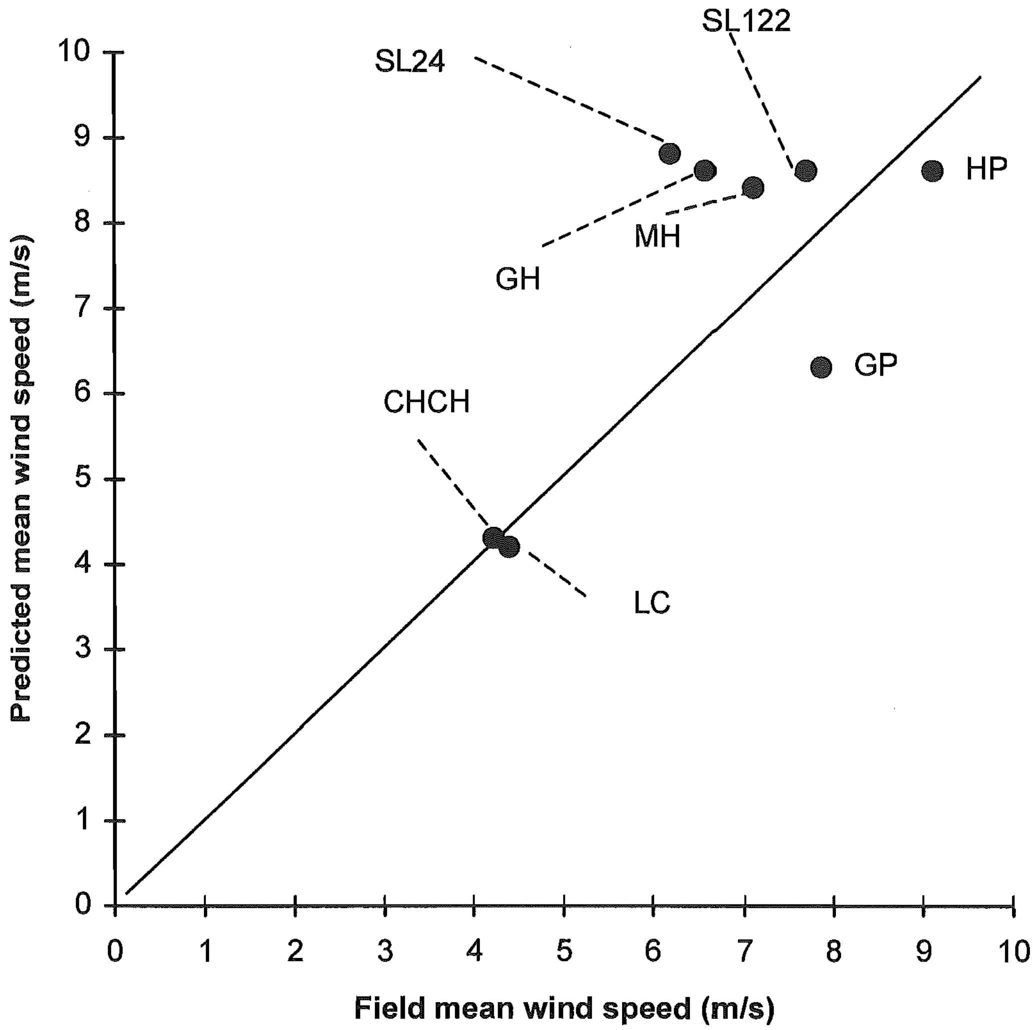


Figure 4.18a. Comparison of mean wind speeds for all directions from field measured data and WAsP predictions (Version 4.0). **Key:**

HP=Herber Peak GP=Gebbies Pass GH=Godley Head
MH=Marley's Hill SL24=Sugar Loaf 24m SL122=Sugar Loaf 122m
CHCH=Christchurch Airport LC=Lincoln College

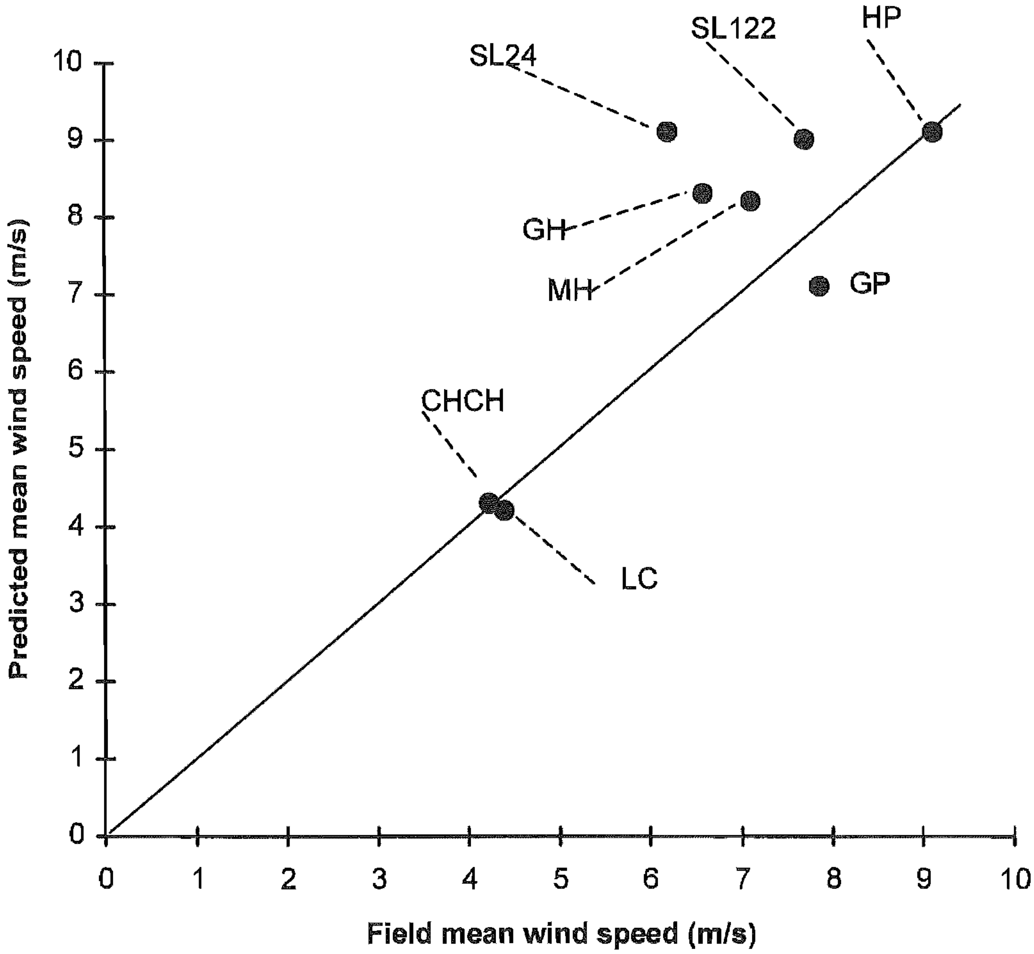


Figure 4.18a. As Figure 4.18a and running WAsP version 4.1.

It is not immediately obvious if the revised WAsP has improved predictions. The new version has seems to cut down the degree of over-estimation at sites with steep slopes at the expense of other sites such as Gebbies Pass with more gentle height gradients. This is clear from graph 18a.

As it was mentioned before, one of the changes in the new version is setting P_{34}[1] parameter (True Up-wind direction in BZ Model) in the *WAsP.par* file from 0 to 1. Another WAsP analysis was run with the new version but setting P_{34} back to 0. It predicted the results shown in Table 4.3, which is the best of all predictions so far. These results were consulted with Risϕ. They advised to use the new version and to set P_{34} back to zero if it produced better predictions. However, it is unknown how one should determine the correct P_{34} setting if there are no field values to compare against.

The remaining WAsP analysis was performed using the latest version V4.1 and P_{34} parameter set to 0. WAsP prediction of mean wind speeds are also compared with site measurement values which have been correlated to the long term wind data at Christchurch Airport by Cherry, 1985. See Table 4.4.

[1] P_{34} determines in which order the perturbations for one sector are combined. When the perturbations are small, it makes no difference if one calculates the speed-up for a sector and then the directional perturbation, or if one does the direction first and then use the speed-up for the turned wind. If the terrain is complex, the perturbations are not small. Setting P34=0 means that the speed-up is calculated and then the directional perturbation.

Table 4.4. Mean wind speeds for all directions from field measurements and WAsP predictions. Values inside brackets represent percentage of over-estimation by WAsP.
Reference wind data: Christchurch Airport, 1960 to 1978 (data excludes calm periods).

	Elevation a.m.s.l. (m)	Anemometer Heights (m)	Field mean wind speed (m/s)	WAsP mean wind speed (m/s)
Christchurch Airport	30	14	4.4	4.5 (2%)
Lincoln College	11	10	4.4	3.9(-11%)
Gebbies Pass	275	10	8.1	7.5 (-7%)
Mount Herbert	917	10	8.9	9.6 (8%)
Sugar Loaf	496 496	24 122	6.2 7.7	9.4 (52%) 9.3 (21%)
Godley Head	245	10	6.4	8.7 (36%)
Marley's Hill	502	30	7.1	8.4 (18%)

Comparing these results with Table 4.1 demonstrate that the combined effect of the revised map and the new WAsP version have reduced the degree of over-estimation. However, WAsP predictions are still high. This is partly because of the absence of the calm periods in the reference wind data for Christchurch Airport.

4.11 LINCOLN COLLEGE SITE AS A REFERENCE SITE

Wind data measured at Lincoln College site during May 1975 to April 1978 was obtained from the Lincoln College Meteorology Department. This data also excludes calm periods. It was rearranged to the WAsP accepted format, see Appendix A2. WAsP prediction of the sites are shown in Table 4.5.

Table 4.5. Mean wind speeds for all directions from field measurements and WAsP predictions. Values inside brackets represent percentage of over-estimation by WAsP.
Reference wind data: 1975-1978 Lincoln Site data (excl. calms).

	Elevation a.m.s.l. (m)	Anemometer Height (m)	Field mean wind speed (m/s)	WAsP mean wind speed (m/s)
Christchurch Airport	30	14	4.4	5.0 (14%)
Lincoln College	11	10	4.4	4.3 (-2%)
Gebbies Pass	275	10	8.1	7.0 (-13%)
Mount Herbert	917	10	8.9	11.5 (29%)
Sugar Loaf	496	24 122	6.2 7.7	11.1(79%) 11.1 (44%)
Godley Head	245	10	6.4	10.2 (59%)
Marley's Hill	502	30	7.1	9.5 (34%)

4.12 MEAN ENERGY DENSITY

Smyth [34] has calculated mean energy flux for: Christchurch Airport, Gebbies Pass, Godley Head, Marley's Hill, and Mount Herbert. These calculations are based on his measurements of 6/1981 - 11/1981. Cherry and Smyth [30] has also estimated a wind energy density of 118 W/m^2 for Christchurch Airport from long term wind data.

WAsP predicted values of mean wind energy density are compared with the field values for above sites. Results are tabulated in Table 4.6.

Table 4.6. Mean wind energy densities compared with results obtained by V Smyth [34]. Values inside brackets are WAsP overestimations.
Reference wind data: Christchurch Airport , June 1981 to November 1981.

	Field mean wind speed (m/s)	**WAsP mean wind speed (m/s)**	**Field mean wind energy density (W/m^2)**	**WAsP mean wind energy density (W/m^2)**
Christchurch Airport	4.23	4.4 (4%)	126.0	116.0 (-8%)
Gebbies Pass	7.87	7.1 (-10%)	769.6	433.0 (-43%)
Mount Herbert	9.12	9.1 (0%)	1069.6	1169.0 (9%)
Godley Head	6.59	8.3 (26%)	519.1	870.0 (68%)
Marley's Hill	7.11	8.2 (15%)	480.8	716.0 (49%)

4. 13 DISCUSSION OF RESULTS

4.13.1 Gebbies Pass

This site has attracted the greatest interest as it has excellent practical potential for wind energy. The pass is significant for its definite convergence of southerly and northerly winds between the Port Hills and the Mt. Herbert range. Through WAsP calculations, this feature was identified by the sector-wise analysis of wind speed-ups.

Table 4.7. Sector-wise speed-ups calculated by WAsP for the Gebbies Pass site.

	Wind Sector Direction											
	North						South					
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
Speed-up (%)	119	156	120	43	-27	27	111	155	127	52	-27	29

Both the southerly (180-240°) and northerly (0-60°) winds are channelled over the saddle with a major increase in the mean wind speeds. The mean wind speed evident in Table 4.3 at this less rugged location has been underpredicted by 10%. Using the long term wind data from Christchurch Airport (which excludes calms) WAsP calculates a value of 7.5 m/s - an under-estimation of 7%. It is interesting to note that WAsP results are consistent using both reference wind data. There are two possibilities to be considered here. Either southerly and northerly winds do not contain significant calm intervals or; the orographic effect of the pass causes even the calm winds to accelerate over the saddle. To investigate the first argument, wind data from the reference site was studied. It was discovered that the most regularly occurred calm periods (winds up to 1 m/s) are from south and north directions (field recordings at Gebbies Pass also support this, see Figure 4.20b). This disqualifies the first reasoning and supports the second point. In fact it is locally well known for Gebbies Pass that 'if there is no trace of wind elsewhere, it's always blowing at the pass'. This feature of Gebbies Pass makes it very attractive to wind energy applications.

Due to the channeling of the winds through the pass, noted earlier, the hill slopes in close proximity to the NE and SW sides of the site would be responsible for most of the orographic effects on the mean wind speed for all wind directions. The effective up-wind slope is approximately 0.2 on the south side and 0.23 on the NE side of the site. Hence, extensive areas of flow separation are not considered likely. Using the practical prediction method described by Taylor and Lee [5], speed-up values could be expected to be between 1.30 and 1.71 of the mean wind speed on flat terrain. The wind tunnel study of this area by Neal et al [32] measured maximum speed-up values for northerly and southerly winds between 1.51 and 1.80. A comparison with WAsP predictions indicates a fair agreement here also, with values of 1.86 for the field measurements and 1.56 for the WAsP predicted mean wind speed-up using reference data from Christchurch Airport for flat and open terrain.

The total energy flux available at this site is estimated by WAsP to be 433.0 W/m^2 at 7.1 m/s mean wind velocity.

Referring to wind data from Lincoln College, WAsP predicts a mean wind speed of 7.0 m/s - 13% less than the field value, see Table 4.5. The Lincoln College site was subjected to location change, and its wind data do not contain calm intervals. Therefore, the higher prediction than the 6 month data set is not totally unexpected.

4.13.2 Mount Herbert

Herbert Peak is the highest point in Banks Peninsula and stands well above the surrounding terrain. Therefore, it is expected that this site behaves like a smooth, isolated hill and should be accurately modeled by WAsP. The predicted wind speed is indeed very close to the field average mean wind speed for the 6 month data set. WAsP prediction is 9.1 m/s compared with the field measured value of 9.12 m/s. Peak speed-up factor of 1.9 is predicted for N-NE sectors.

WAsP prediction is slightly over using the longer term data from Christchurch Airport (ex-calms). WAsP estimates a mean wind speed of 9.6 m/s which is only 8% higher than the field value reported by Cherry and Smyth [30].

Using the alternative reference wind data record at Lincoln College site, WAsP predicts a higher wind speed (11.5 m/s) at this site which is 29% higher than the actual measured field mean wind speed, higher than expected. Cherry and Smyth [30] also categorise Mt. Herbert as an isolated hill and show that this site is subjected to a different wind regime to that of Christchurch Airport. Field measurements confirm that Mt. Herbert is subjected to a highland type wind regime where as lowland type winds are perpetual to Christchurch Airport, see Figure 4.21.

Figure 4.19 show how diurnal mean wind speeds at Mt. Herbert are closely related to 900m wind data at Christchurch Airport. These could suggest that any relationship might be complex and beyond current numerical prediction techniques.

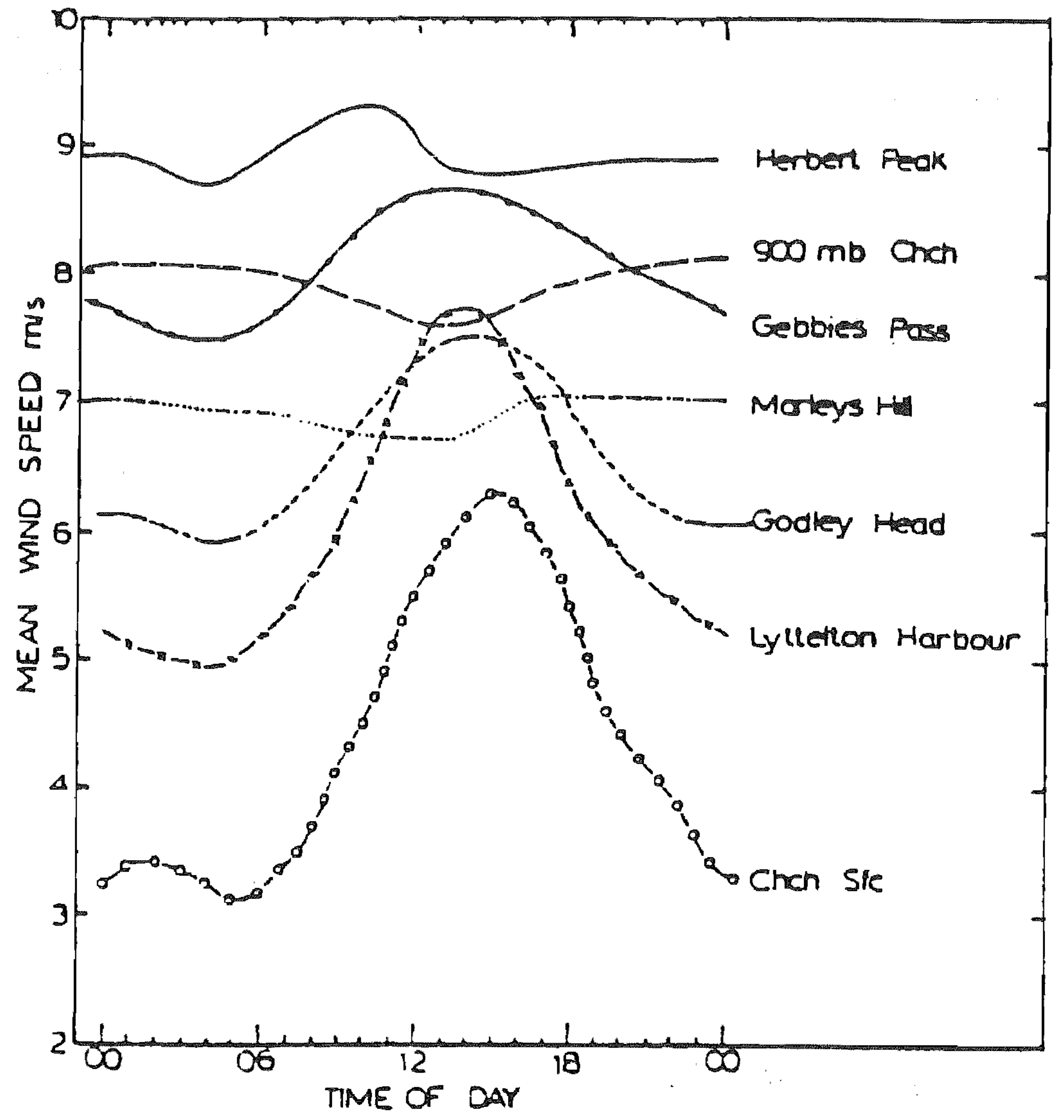


Figure 4.19. Diurnal mean wind speeds at typical Canterbury sites.

4.13.3 Sugar Loaf

Smyth [34] has not included this site in his 1981 field study. However, there are unique measurements at this site for two different heights, 24 m and 122 m above the local ground level. Cherry and Smyth [30] have used long term wind data at Christchurch Airport to correlate the Sugar Loaf wind survey to the long term mean climate. Using the reference data record at Christchurch Airport (ex calms), WAsP estimation of wind speeds at heights of 24m and 122m are 9.4 and 9.3 m/s, respectively. The predicted wind speed-height profile is almost uniform above 20m with the predicted sector speed-up values reaching 1.13 - 1.34 at lower levels. A uniform velocity profile is often found over steep ridges and summits but the field measurements unexpectedly show evidence of strong shear. As a consequence, there is a 52% over-estimation of the predicted mean wind speeds at the low land level and 21% at the higher level. The steep slopes on the SE side would cause separated flows close to the ground and the low land level anemometer could well be frequently immersed in this modified flow. In addition, the shadow effect of the lattice tower on which the instruments were mounted could be significant for some wind directions.

Wind data from the Lincoln site give higher predictions (11.1m/s for both heights), an overestimation of 79% and 44% for 24m and 122m a.g.l, respectively. It needs to be noted again that reference wind data from Christchurch Airport and Lincoln site did not include calms whereas calm periods have been inter-correlated into the site wind climate. This is partially responsible for the WAsP excessive over-estimation at this site. However the reliability of any comparison at this site is not as good as the other sites as the field record length is unknown and the reference data for the WAsP predictions are from longer term airport data record.

4.13.4 Marley's Hill

The shorter term wind data from Christchurch Airport predicted a wind speed of 8.2 m/s, 15% higher than the 7.11 m/s observed from field data. The longer term wind data from the airport and Lincoln College gave higher predictions, by 18% and 34%, respectively.

Marley's Hill has a rounded peak and does not have the steep slopes to the harbour like its neighbour Sugar Loaf. It is expected that the wind direction at the summit would be influenced by channeling through the harbour which lies on a NE-SW axis and the flows remaining attached. WAsP calculation of speed-ups at the anemometer height predicts a fairly uniform flow acceleration over the hill for all wind sectors. See Table 4.8.

There is a stand of 20m high trees to the north of the site which is likely to provide shelter from the NW direction. A surface roughness length of 0.1 m was assigned to the peak and 0.02m to the surrounding slope. This value agrees with typical roughness length classes suggested by WAsP. It is more than fifteen years since the recordings of field data and assigning a true surface texture figure to simulate the site at that time is not easy.

Table 4.8. Sector-wise speed-ups calculated by WAsP Marley's Hill.

	Wind Sector Direction											
	North						South					
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
Speed-up (%)	82	66	78	104	118	108	82	66	78	104	118	108

4.13.5 Godley Head

This is an outlying site of low priority and the need for efficiency in allocating contour data points forced the use of coarse height intervals (50 and 100m) in this area, so that the terrain is not accurately modeled. However, WAsP over-predictions are not entirely surprising. The longer term data from Lincoln and Christchurch sites produced 59% to 36% flow speed overestimations. This stresses the requirement of accurate maps with high contour resolutions at the sites for reliable results.

4.14 GENERAL DISCUSSION

4.14.1 Thermal effects and sea breezes

Christchurch Airport is located about 10km inland from the coast, whereas the sites under study are typical coastal hill sites which are not likely to have neutrally-stable conditions unless strong wind conditions occur. The wind flow across the area of study could also be entirely uncorrelated under certain conditions such as thermal stratification. The WAsP program does not take into account thermal effects in the flow analysis. Under such conditions, the airport may have calm conditions, but coastal hill sites could experience a developing sea breeze at low level or strong high level winds on the ridge tops. Cherry and Smyth [30] have identified such strongly uncorrelated wind speeds between Mt. Herbert and surrounding low level sites.

Monthly mean wind speeds at this elevated site increase over winter in a similar manner to 900mb winds taken at Christchurch Airport. This behaviour is in contrast to the low level sites which exhibit a summer peak in the wind speeds at Mt. Herbert which change little throughout the day. This is in contrast with the marked afternoon peak in the hourly mean wind speed for low level sites due to the strong NE sea-breeze influence throughout the whole area. See Figure 4.8. An additional complication in the area is reported by Cherry and Smyth [30] in the form of a frequently occurring low level maximum in the mean wind speed-height profile below 200m that was discovered from radar measurements.

4.14.2 Thermal Inversion

BZ model (used in the WAsP Orography Model) is based on neutral stratification. It includes an inversion height z_i and a strength parameter (parameter #6 and #7 in the *WAsP.par* File) to enable an extremely simple modeling of the climatological effect of the stably stratified atmosphere above the boundary layer. Horizontal scales larger than z_i are squeezed to make the calculated velocity perturbations more horizontal and attenuate vertical motion. The inversion height is set to 1000m (for all seasons) and, for this study, all WAsP analysis are performed with this setting.

The softness factor (parameter #7) governs the strength of this effect and relates to the intensity of thermal inversion. For maximum squeezing #7 is set to zero. The default value is 1 where the inversion has no effect at all. All WAsP calculations performed with the default value since any lesser value gives higher overestimations. Table below displays WAsP predictions for the Port Hills sites at z_i = 1000m and #7=0.8.

Table 4.9. Mean wind speeds for all directions from field measurements and WAsP predictions. Values inside brackets represent percentage of over-estimation by WAsP relative to the field data.
Reference wind data: Christchurch Airport, June 1981 to November 1981 - data includes calm periods.

	Field mean wind speed (m/s)	WAsP mean wind speed (#7=1.0) (m/s)	WAsP mean wind speed (#7=0.8) (m/s)
Christchurch Airport	4.23	4.4 (4%)	4.4 (4%)
Lincoln College	4.4	4.0 (-9%)	3.8 (-14%)
Gebbies Pass	7.87	7.1 (-10%)	7.1 (-10%)
Mount Herbert	9.12	9.1 (0%)	9.5 (4%)
Sugar Loaf	6.0 7.4	9.1 (52%) 9.0 (22%)	9.2 (53%) 9.1 (23%)
Godley Head	6.59	8.3 (26%)	8.3 (26%)
Marley's Hill	7.11	8.2 (15%)	8.2 (15%)

In the adequate use of WAsP it is important, if possible, to verify the predictions by using simultaneous measurements from several reference stations (e.g. Christchurch Airport and Lincoln College). This permits the choice of the best values of physical parameters in the Parameter File (if not available from the field data), which can exert great influence on the results.

4.15 PORT HILLS SITES UNDER STRONG WINDY CONDITIONS

In order to eliminate the effects of thermal stratification and assuring neutral stable conditions one should examine the sites during the strong windy situations. Smyth [34] documented maximum wind speeds observed at the selected sites on the Port Hills. Hourly wind speed and direction readings for the same interval were also obtained from NIWA. The results are shown in Tables 4.10 and 4.11.

Table 4.10. Maximum observed hourly mean wind speeds for the selected sites. Source: V. Smyth.

Site	Max observed hourly mean (m/s)	Prevailing sector (°)	Date of observance
Gebbies Pass	36.4	180	7/11/1981
Godley Head	31.9	230	26/8/1981
Mt. Herbert	38.3	300	10/10/1981
Marley's Hill	26.7	220	26/8/1981
Christchurch Airport	16.0	100	23/8/1981

Table 4.11. Maximum observed hourly mean wind speeds at Christchurch Airport. Source: NIWA

Date	Max observed hourly mean (m/s)	Prevailing sector (°)
7/11/1981	13.4	190
10/10/1981	8.8	330
26/8/1981	15.4	240
23/8/1981	6.7	100-110

Examining data in Tables 4.10 and 4.11 clearly verifies that wind speeds at the selected site on the Port Hills do not entirely correlate to Christchurch Airport wind data. Hence, thermal effects and coastal sea breezes (could be a northerly wind not covered in Table 4.10) play an important role in this region's wind climate. For example, the highest wind speed recorded for Mt. Herbert (in the 1981 survey) is 38.3m/s which occurred on 10 October when moderate windy conditions exist at Christchurch Airport with a maximum wind speed of 8.8m/s.

There is a slight complication in field data in reporting the maximum hourly wind speed at Christchurch Airport. Smyth [34] reports a maximum wind speed of 16 m/s on 23 August blowing from the 100° (SE) direction. But data from NIWA refers to 26 August for a wind speed of 15.4 m/s from 240° (SW) direction. Smyth's [34] field measurements observe a peak wind speed of 31.9 m/s for Godley Head and 26.9 m/s for Marley's Hill on the same day that NIWA reports the maximum wind speed for Christchurch Airport. All these observation are from SW direction. Godley Head is a fairly exposed site and would be expected to have the same wind regimes as Christchurch Airport. It also seems unusual for gusty winds from SE direction at this time of the year. Therefore, NIWA's observation for peak wind speed at Christchurch Airport is more creditable than the Smyth's recording.

Gebbies Pass maximum wind speed occurs on 7 November when winds of 13.4 m/s have been recorded at Christchurch Airport. This further indicated that this site is also subjected to the low level winds, as also suggested by Cherry and Smyth [30]. The reported direction of prevailing winds on this day for both sites are quite agreeable, both from the south.

4.15.1 WAsP Application

The WAsP Package is applied to predict mean wind speeds at the Port Hills sites during strong wind conditions. An attempt was made to process the wind data at Christchurch Airport recorded on 26 August 1981 when the maximum wind speed is observed. The strong windy spell only occurs for a couple of hours and it then drops considerably for the rest of this day. This causes WAsP to calculate a lower mean wind velocity (10.8m/s) for this day. To remove the effect of the low readings on this day, the wind data are arranged to read a wind speed of 15.4 m/s from 240° direction for all hourly recordings. Hence, the mean wind speed at Christchurch Airport is calculated by WAsP to be 14.8 m/s.

WAsP predictions at the Port Hills sites, using this reference wind data, are shown in Table 4.12.

Table 4.12. Maximum wind speeds predicted by WAsP for the selected sites on the Port Hills.

Sites	**Max hourly mean wind speed (m/s)**	
	V Smyth	**WAsP**
Christchurch Airport	16.0	14.8
Gebbies Pass	36.4	16.6
Godley Head	31.9	24.1
Herbert Peak	38.3	26.9
Marley's Hill	26.7	26.2
Sugar Loaf - 24m	--	27.9
Sugar Loaf - 122m	--	24.1
Lincoln College	--	12.6

WAsP predictions are quite inconsistent. The only close prediction happens for Marley's Hill. WAsP has also calculated the reference wind speed (14.8 m/s) slightly lower than the actual value in the time series data (15.4 m/s). It has underestimated wind speeds for all other sites, particularly Gebbies Pass. This was thought to be because of the prevailing wind direction in wind atlas data set, which is formed from an omnidirectional time series - 240° (SW) sector only. This sector is slightly out of line with the direction of wind channeling by Gebbies Pass which lies on a N to S axis (winds from the south and north sector are funneled through and accelerated over the pass). Using the same wind speed (15.4 m/s), another wind atlas set was made with the wind directions from the south and north only. WAsP prediction was lower than the previous attempt. In fact, its estimation for Gebbies Pass was 14.8 m/s.

The degree of underestimation is also considerably high for Herbert Peak. This clearly demonstrate that, during strong wind conditions, this site is subjected to a different wind regimes than Christchurch Airport. For this site, maximum hourly wind speed was recorded on 10th of October, a totally different time from that of Christchurch Airport (26 August).

This exercise demonstrates that the effects from stratified and other unstable and uncorrelated atmospheric conditions lie beyond the capability of WAsP. Forming a wind atlas data set from a very limited wind recordings proved difficult for WAsP. For instance, there were only 24 recordings in the wind file for the 26 August observations at Christchurch Airport. However, WAsP counted as many as 1000 recordings when it calculated the wind histogram table! Generally, WAsP has been designed to make wind atlas information form wind recordings for longer periods, six months to several years.

4.16 SITE CROSS PREDICTIONS

During the 1981 survey, Smyth recorded a limited amount of hourly wind speed and direction readings at Gebbies Pass, Herbert Peak, Marley's Hill, Godley Head, and Christchurch Airport. Wind data at each site are used by WAsP to predict mean wind speeds at other sites. WAsP results are shown in Table 4.12. Results are presented in a score scheme (Troen and Petersen [3]). The first column contains the predicted and the first row the predictor stations. The actual measured values for each site are inside brackets.

Table 4.13. Measured and estimated wind speeds for selected sites at anemometer heights.
Reference wind data: V Smyth 1981 (June - November) survey.

	Gebbies Pass	**Herbert Peak**	**Marley's Hill**	**Godley Head**	**ChCh Airport**	**Sugar Loaf 24m**	**Sugar Loaf 122m**
Gebbies Pass	7.5(7.9)	5.4	6.1	5.1	7.1	--	--
Herbert Peak	12.6	8.8(9.1)	8.2	6.8	9.1	--	--
Marley's Hill	11.3	9.4	7.0(7.1)	6.2	8.2	--	--
Godley Head	11.4	8.3	7.4	6.2(6.6)	8.3	--	--
ChCh Airport	5.7	4.6	3.8	3.3	4.4(4.2)	--	--
Sugar Loaf 24	13.1	10.4	8.0	6.9	9.1	--	--
Sugar Loaf 122	12.4	10.0	8.0	6.8	9.0	--	--

Predictions by WAsP of the mean wind speeds for all site combinations show greater magnitude of error than the previous case when a flat featureless site (eg Christchurch Airport or Lincoln College) was used to generate the reference wind atlas file. WAsP predictions for self predicted sites are all under the actual values by 1-7%, unlike the Christchurch Airport and Lincoln College predictions which were quite close to the field data.

There is only one adjustment which could be made to the input data in order for WAsP to calculate higher values. And this is to lower the roughness length values assigned for each site. However, assignment of surface roughness values for each site have been made in accordance with the practical knowledge and previous wind tunnel studies of this region; lowering them seems to be an impractical move. Nevertheless, it was tried to see the results. As a matter of fact, it did not alter WAsP predictions much.

Generally, it is difficult to establish a pattern for WAsP predictions. Gebbies Pass, in particular, produced unrealistic results both as a predictor and predicted site. This site predicted the wind speeds for all other sites higher than the recorded field measurements. In contrast, all other sites predicted much lower wind speeds at Gebbies Pass. It seems that estimation errors get larger with the height differential between the predictor and predicted sites. For instance, WAsP over-predictions are much more severe when Gebbies Pass data are used to estimate the mean wind speed at Herbert Peak than when Marley's Hill predicted for Herbert Peak.

There are other influential elements such as the analysis and application procedures of WAsP in generating a wind atlas file and the cross-correlation between sites that can offer further reasoning in WAsP miss-predictions, Bowen and Mortensen [37]. Consider first the WAsP Application procedure applied using generalised wind data from Christchurch Airport to generate the atlas file. WAsP over-estimation of rugged sites on the Port Hills were well observed and partly related to the atlas file fictitious representation of the reference site which is flat, and featureless and approximates the Christchurch Airport site description. However, WAsP over-predictions were not severe and, perhaps in some sense, were explainable. In this exercise, the reference sites are not flat any more. They are rugged with steep slopes leading to the summits. The WAsP linear orographic model which is limited to neutrally-stable wind flows over low and smooth hills has to cope both with hilly terrain at the reference and the predicted sites on the hills. This intensifies the error magnitude - discussed later in chapter 5 .

Last, the cross-correlation factor is another important component contributing to WAsP errors. Accurate WAsP predictions may be obtained when both the reference and predicted sites are subjected to the same weather regime. Results of the previous exercise revealed that the sites on the Port Hills are not always subjected to the same weather pattern.

4.17 WIND FREQUENCY DISTRIBUTIONS

Sector-wise frequency of wind occurrence at the selected sites are shown in Figures 4.20 to 4.23. Figures (a) show wind distributions calculated from Christchurch Airport reference wind data, and Figures (b) are self-predicted wind distributions from field recordings. Comparing Figures (a) with Figures (b) show that there exists a marked pattern between two distributions for low level sites. For Gebbies Pass, Godley Head, and perhaps Marley's Hill wind distributions calculated from Christchurch Airport wind data bear close resemblance to the distribution from the sites' own wind data. This resemblance is more precise for Godley Head.

For Gebbies pass, the northeasterly winds are turned slightly anti-clockwise as they are channeled through the pass. WAsP has failed to predict this turning feature of the pass. Figure 4.20b shows the turning effect by the pass as 0° and 330° sectors contain considerable wind occurrences. Distribution in Figure 4.20a is very similar to the Christchurch Airport self-predicted wind frequency in Figure 4.16a.

The recorded field data for Marley's Hill (Figure 4.22b) show that this site enjoys well distributed and sustained winds from all directions. WAsP predictions (Figure 4.22a) show a similar pattern. Comparing Figure 4.21b with 4.22b, it becomes apparent that Marley's Hill site exhibits elevated sites wind pattern like Herbert Peak. This feature has also been picked up by Cherry and Smyth [30].

The sector-wise frequency of wind occurrence at Herbert Peak calculated from its own wind data show a typical high level site distribution with strong sea breezes and dominant northwesterlies. WAsP predictions from the Christchurch airport (which is a typical low level site) for this site also roughly follows the same pattern.

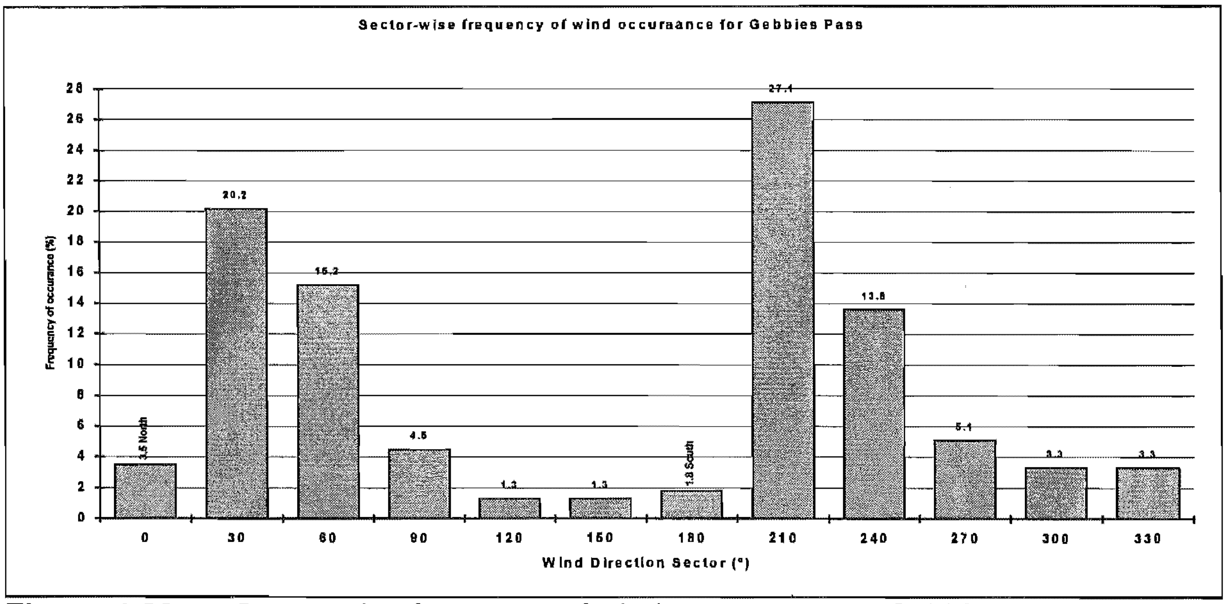


Figure 4.20a. Sector-wise frequency of wind occurrence at Gebbies Pass calculated by WAsP using wind data from Christchurch Airport. (Period: June - November 1981).

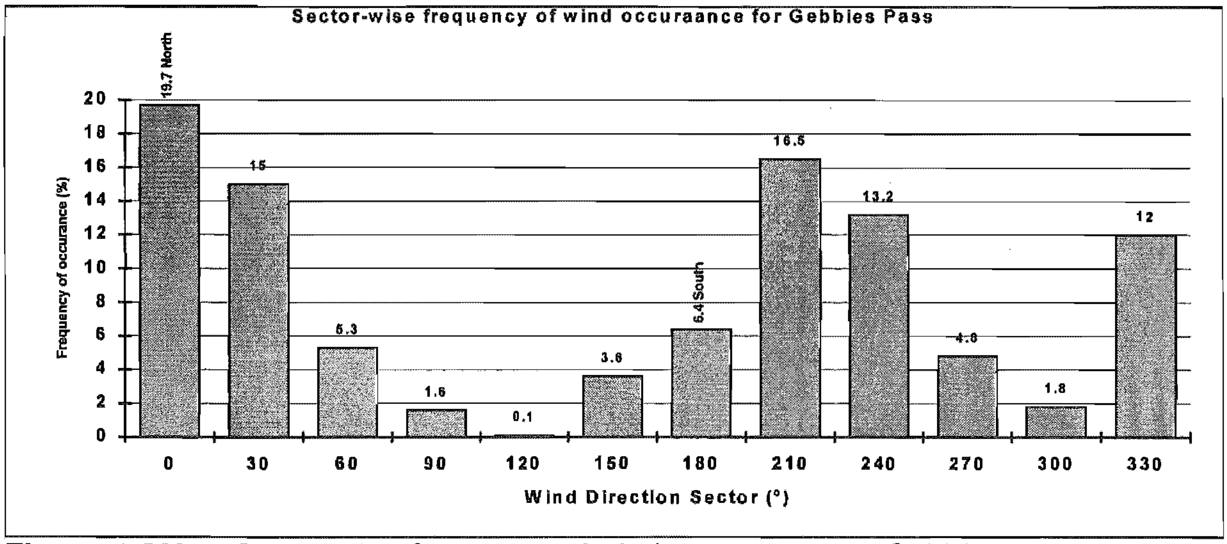


Figure 4.20b. Sector-wise frequency of wind occurrence at Gebbies Pass calculated by WAsP using wind data from Gebbies Pass. (Period: June - November 1981).

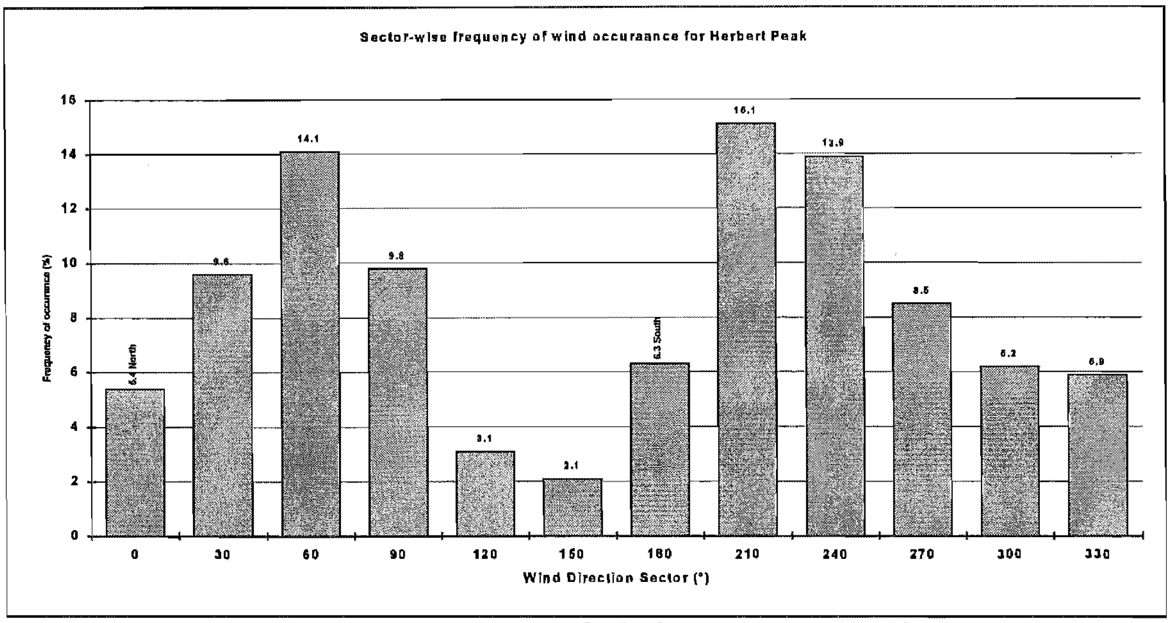


Figure 4.21a. Sector-wise frequency of wind occurrence at Herbert Peak calculated by WAsP using wind data from Christchurch Airport. (Period: June - November 1981).

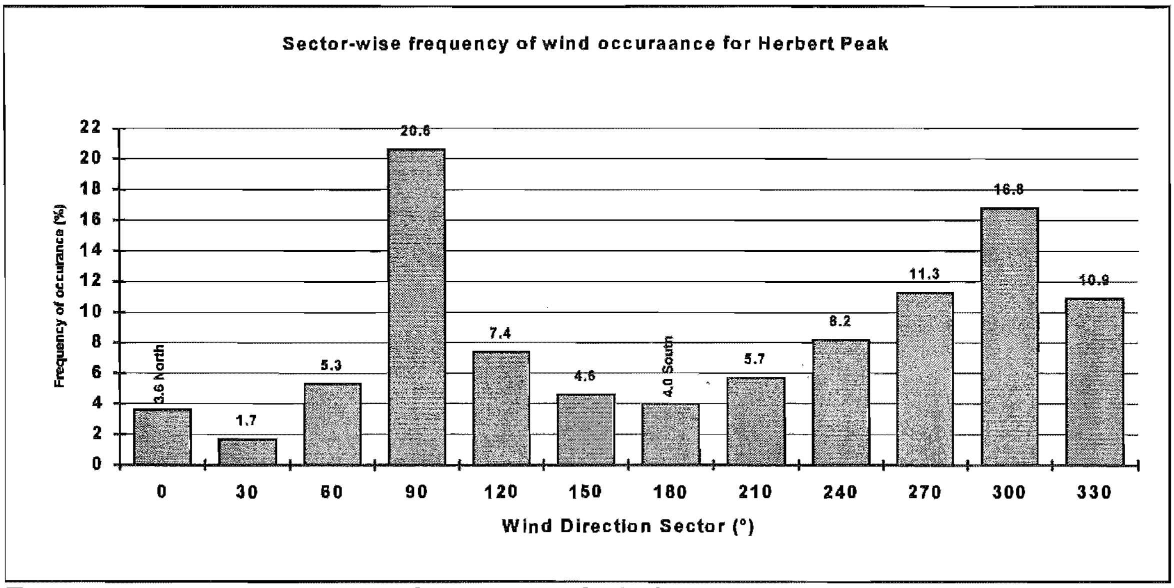


Figure 4.21b. Sector-wise frequency of wind occurrence at Herbert Peak calculated by WAsP using wind data from Herbert Peak . (Period: June - November 1981).

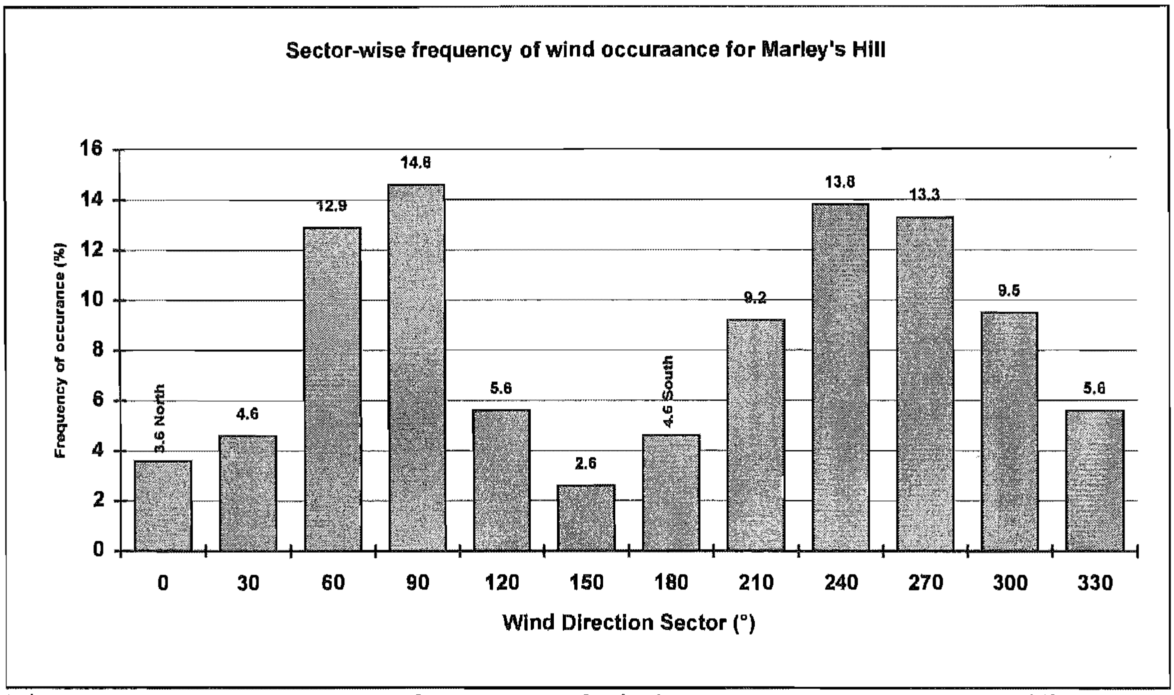


Figure 4.22a. Sector-wise frequency of wind occurrence at Marley's Hill calculated by WAsP using wind data from Christchurch Airport. (Period: June - November 1981).

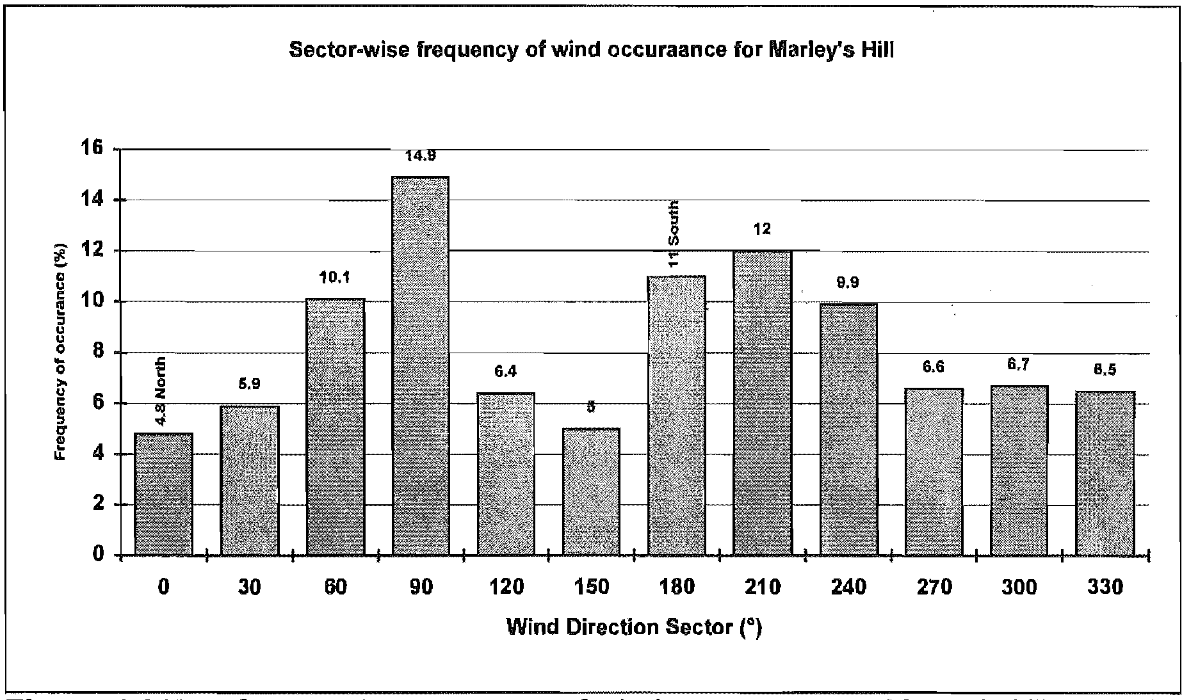


Figure 4.22b. Sector-wise frequency of wind occurrence at Marley's Hill calculated by WAsP using wind data from Marley's Hill. (Period: June - November 1981).

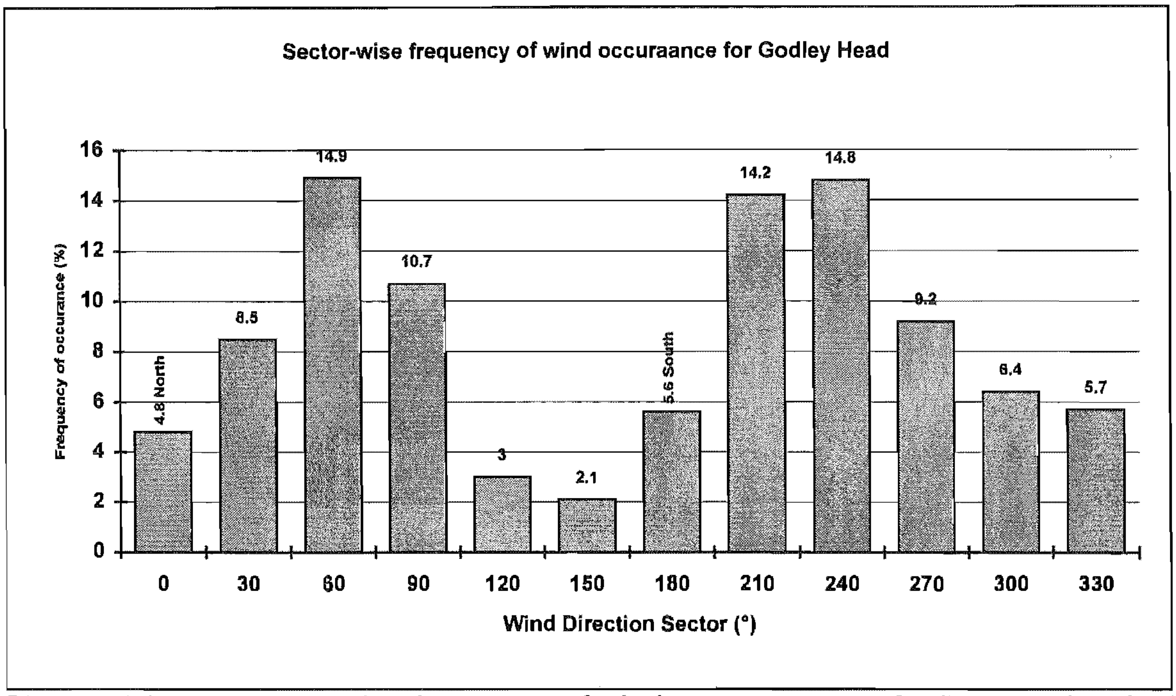


Figure 4.23a. Sector-wise frequency of wind occurrence at Godley Head calculated by WAsP using wind data from Christchurch Airport. (Period: June - November 1981).

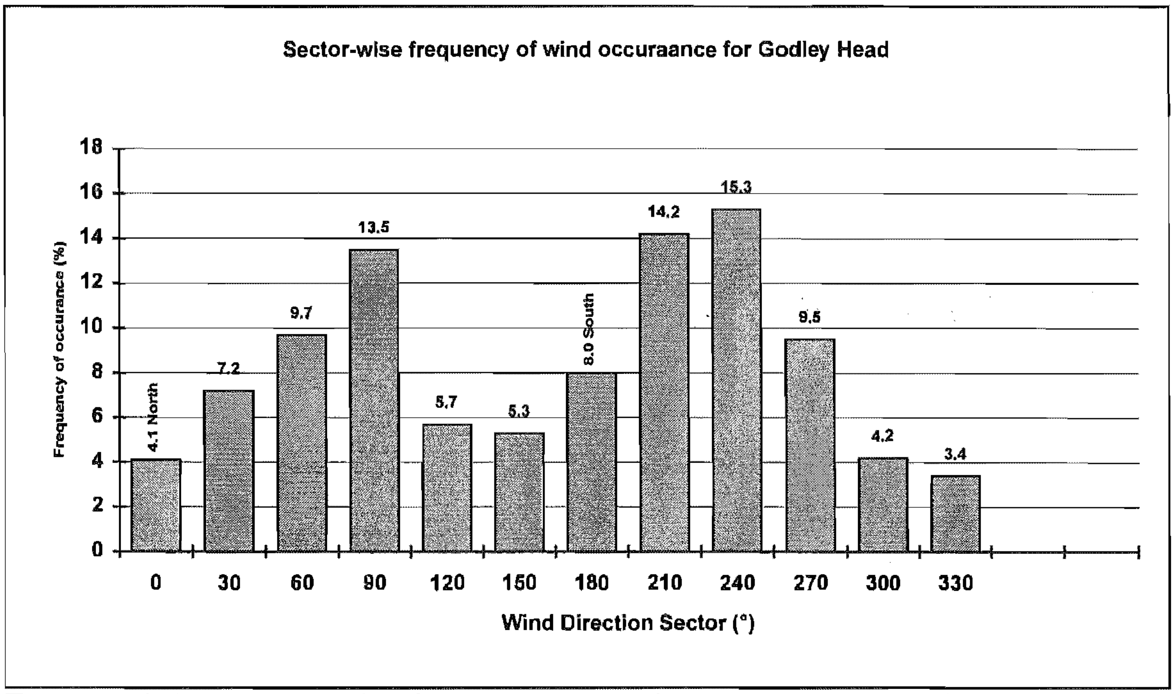


Figure 4.23b. Sector-wise frequency of wind occurrence at Godley Head calculated by WAsP using wind data from Godley Head. (Period: June - November 1981).

4.18 WIND VELOCITY PROFILES CALCULATED BY WAsP

Figure 4.24 to 4.28 show vertical profiles of the speed-up for each site for NE (30° sector). All sites produce speed-ups in excess of 100% for elevations less than 10m a.g.l. Winds over Gebbies Pass speed up suddenly from 1m to 2m a.g.l. and remain strong until 50m a.g.l. (over 50% until 80m), see Figure 4.24. Medium size wind turbines (up to 750kW) harvest their wind energy at a hub height of 40m to 75m a.g.l. This makes this site an excellent candidate for wind energy applications since the N- E and S-SW directions are the prevailing wind directions at Gebbies Pass.

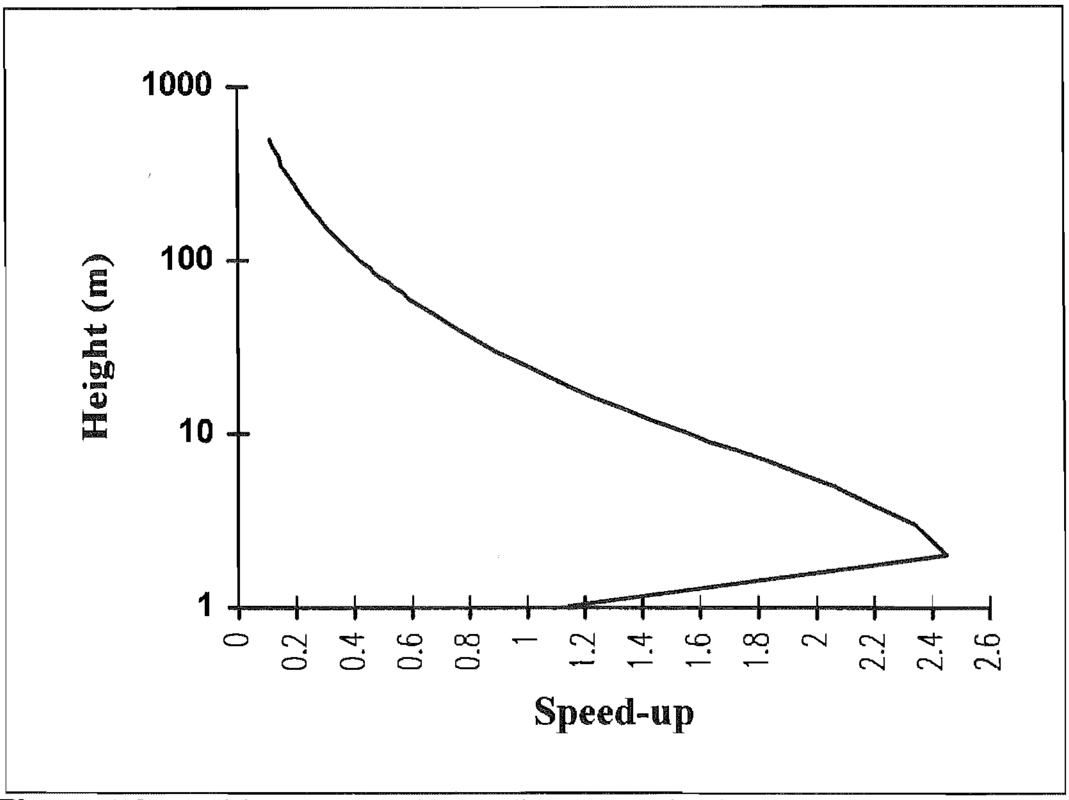


Figure 4.24. Vertical velocity profile at Gebbies Pass for NE (30° sector) direction.

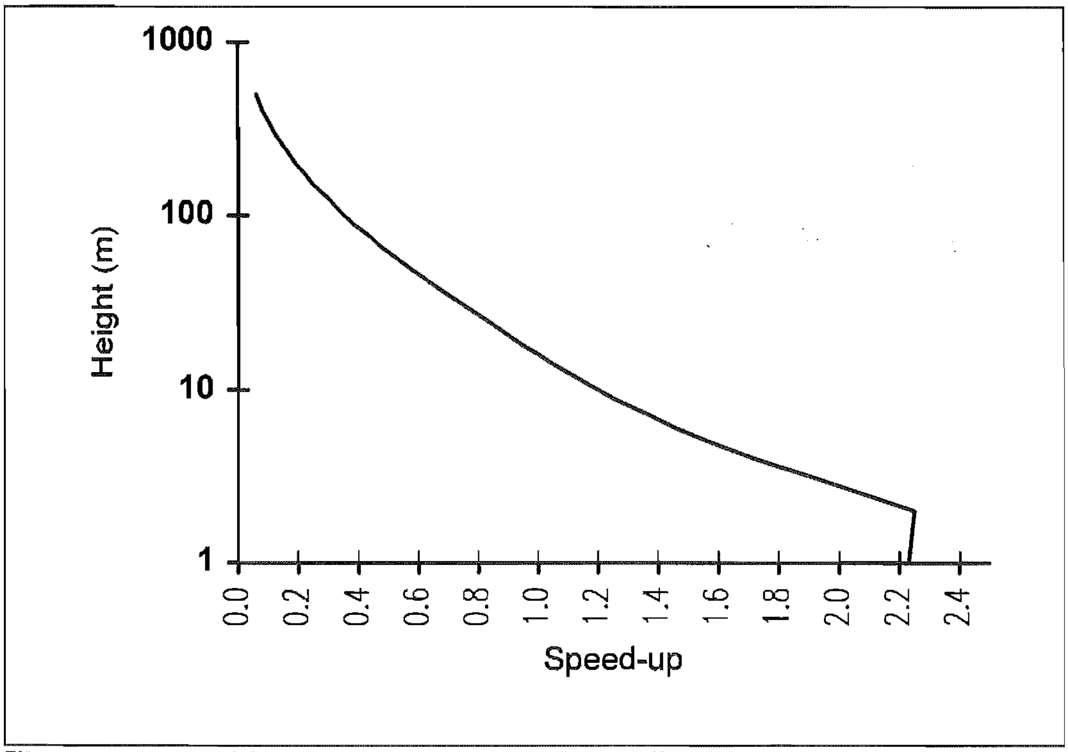


Figure 4.25. Vertical velocity profile at Godley Head for NE (30° sector) direction.

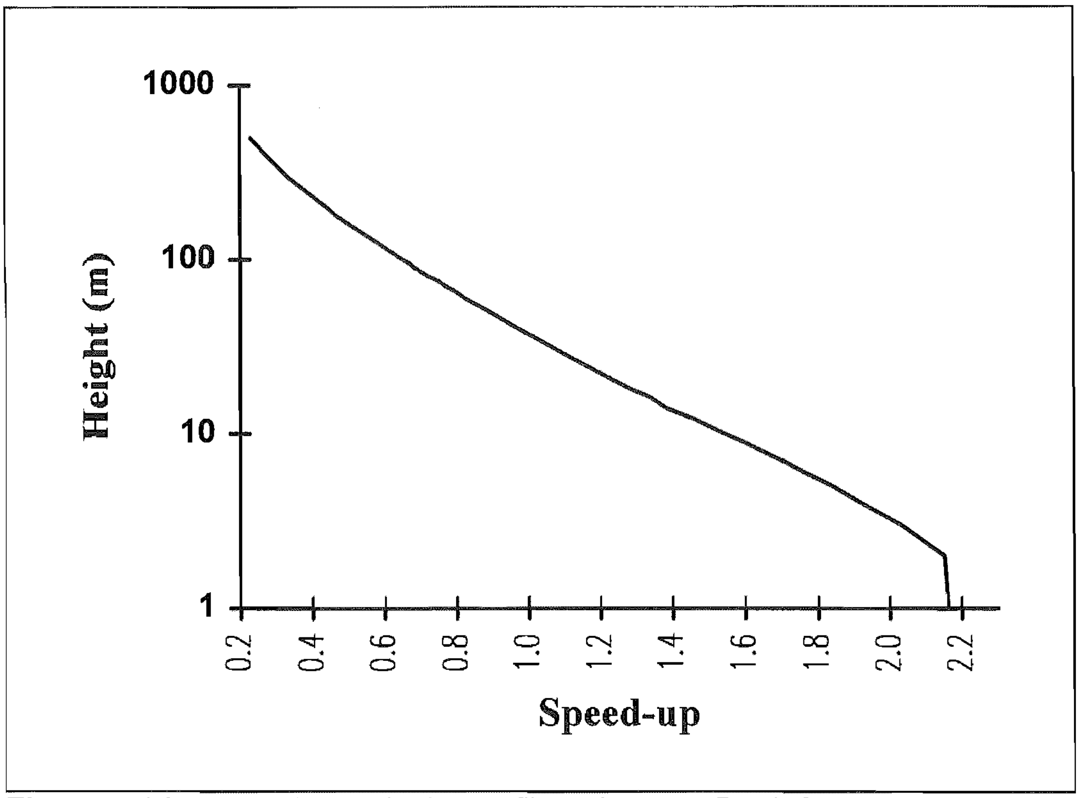


Figure 4.26. Vertical velocity profile at Herbert Peak for NE (30° sector) direction.

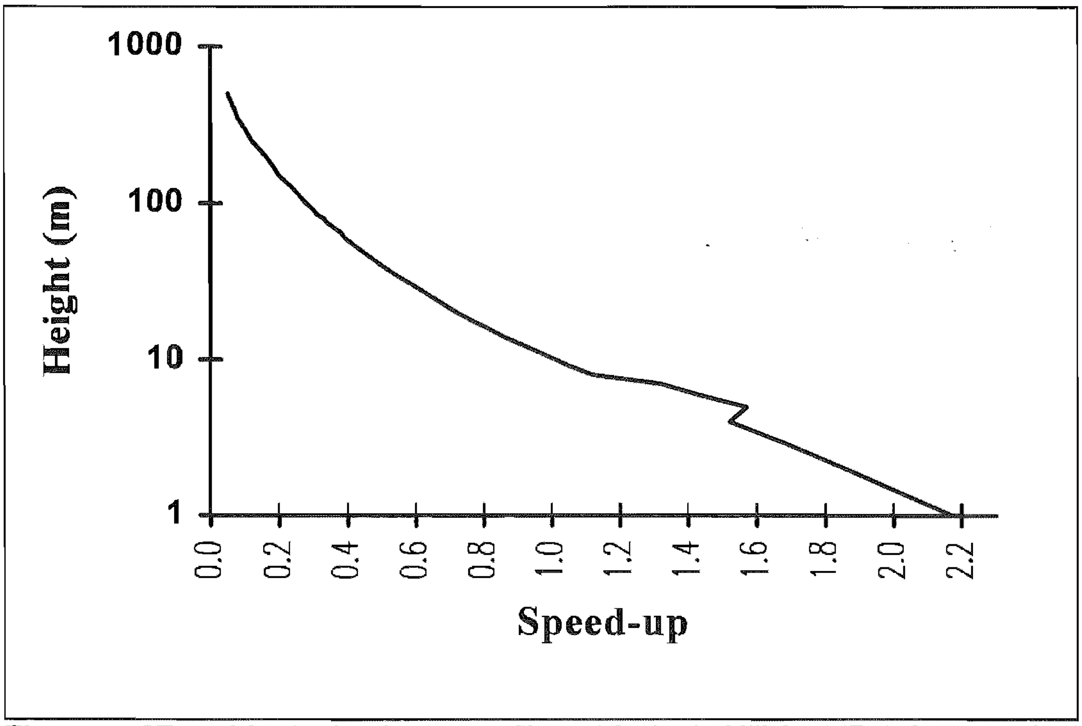


Figure 4.27. Vertical velocity profile at Marley's Hill for NE (30° sector) direction.

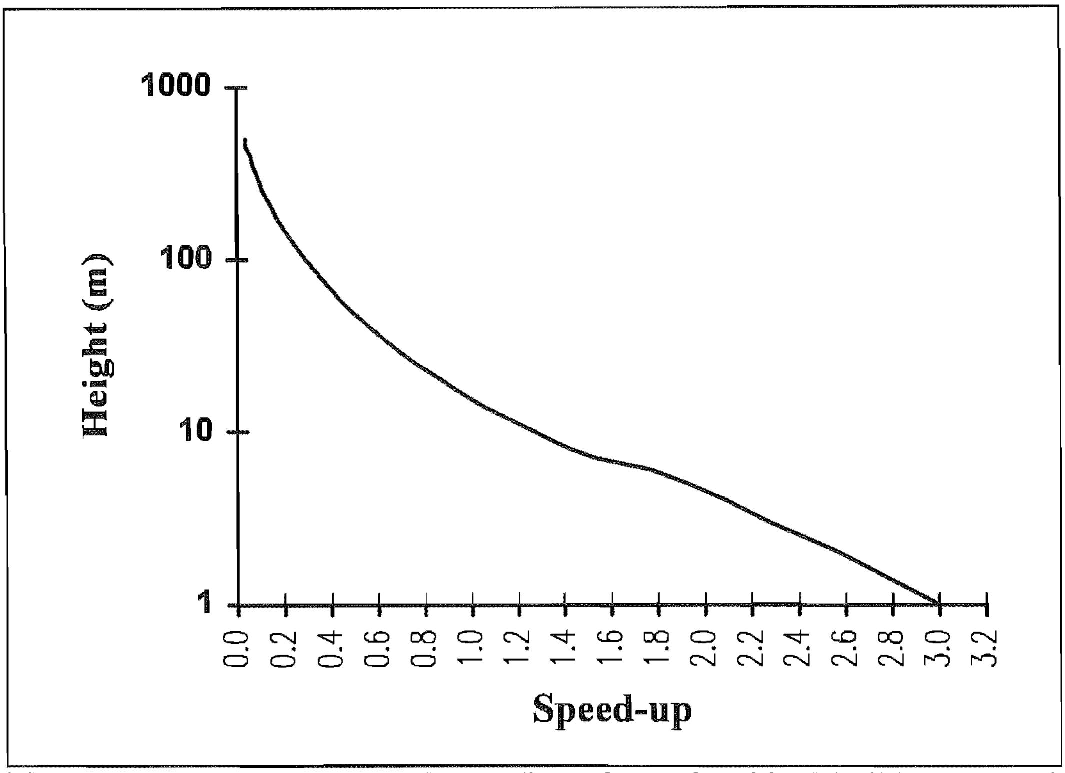


Figure 4.28. Vertical velocity profile at Sugar Loaf for NE (30° sector) direction.

Herbert Peak and Godley Head profiles are similar, but Herbert Peak speed-up values are stronger with steeper slope, Figures 4.25 and 4.26. Herbert Peak values remain above 50% until 150m elevation and decreased only to 23% for 500m a.g.l.

At Sugar Loaf summit speed-up values are strong for elevations close to the ground and hence higher wind shear for this wind direction. Wind speed-up at the anemometer height of 24m is 78% and then uniformly drops to 25% for the 122m height, a considerable reduction. However, the mean wind velocity at these two anemometer heights are predicted by WAsP to be almost equal, see Table 4.3.

Marley's Hill profile is similar to Sugar Loaf's but starting at a lower value. There seems to be a calculation discrepancy for height of 6m a.g.l. This could well be a co-proccessor error as no other reason could be found.

4.19 CONCLUSIONS

WAsP predictions of sites on the Port Hills demonstrate WAsP limitations. Its reliability is highly dependent to the accuracy of map data, the ruggedness at a site, and to the level of atmospheric correlation between the reference and predicted sites. If a flat and featureless site is used as the reference site, WAsP estimation for the reference site is very close but tends to always over-predict wind speeds at sites with slopes greater than 0.3.

In the Port Hills analysis, WAsP predictions were best at Herbert Peak and Gebbies Pass when Christchurch Airport was the reference site. Over-prediction at Marley's Hill and Sugar Loaf is partly related to unattached flows (caused by steep slopes) and different atmospheric conditions. Inadequacy of data in the map file was one of the contributing factors for poor predictions at Godley Head.

In the cross-prediction exercise, it was difficult to establish a pattern for WAsP predictions. Gebbies Pass, in particular, produced unrealistic results both as a predictor and predicted site. It seems that estimation errors get larger with the height differential between the predictor and predicted sites. However, WAsP errors are the subject of the next chapter which discusses them more fully.

CHAPTER V

WAsP ERRORS IN WIND ENERGY PREDICTIONS

5.1 INTRODUCTION

The strengths and weaknesses of WAsP in predicting wind statistics were demonstrated in the previous two chapters. It was shown that WAsP mis-predictions are closely related to terrain steepness and climate complexity. In this chapter, it is investigated to see if WAsP errors could be quantified by the effect of these terrain features. This is based on a technique developed by Bowen et al [38]. In this technique, two indicators are proposed which are based on the difference in ruggedness and the cross-correlation coefficient of the reference and predicted sites, respectively.

The ruggedness indicator which is referred to as Ruggedness Index (RI), is looked at here and its results are compared with the Port Hills field data.

5.2 WAsP PREDICTION ERRORS

WAsP errors could be kept to a minimum if the operational limits are not violated by factors associated with the atmospheric conditions and the terrain. Askervein Hill results is a proof of this where terrain is smooth and isolated and wind flow over the hill is very much attached except on the lee side. The WAsP prediction model works as a transfer function which correlates the wind speeds at the predicted sites to the reference site. WAsP predictions are reliable so long as the WAsP assumption of a uniform speed-up factor between the two sites for each wind direction sector is maintained. This speed-up factor is calculated and assumed to be unrelated to climatic conditions. However, the reality of wind farming realises different terrain and climate conditions. Majority of candidate sites are located in hilly terrain and prevailing weather conditions are fairly complex. The size of any error by WAsP is dependent on the degree that the operational limits are violated by factors associated with the atmospheric conditions and topography.

Application of WAsP to the sites on the Port Hills shows that prediction errors are related to the terrain surrounding the reference and predicted sites. The magnitudes of these errors are influenced by extensive flow separation, the degree of turning in each sector (eg. Sugar Loaf) and the accuracy of map in terms of contour resolution (eg. Godley Head). Hence, more complex terrain causes a greater degree of flow separation near the site and this leads to bigger WAsP errors as the flow becomes more detached from the hill surface. To analyse the magnitude of the error caused by terrain ruggedness, one attempt is to quantify the degree of separation which is mainly caused by steep slopes greater than about 0.3 gradient. Therefore, one could estimate the plan area of the map surface which has a gradient greater than 0.3 (0.3 is the slope limit above which separated flow is likely to occur). Obviously this method is very rough and insensitive to the nature of the terrain. Consider sites (a) and (b) in Figure 5.1, which have the same plan area and both violate 0.3 threshold, say, by 20%. Although both hills will have the same RIX value (see section 4), the wind flows and separated flow regions are very different. For example, site (a) causes a positive speed-up at its peak where as site (b), which consists of a number of small hills, has much less overall speed-up effect on the flow.

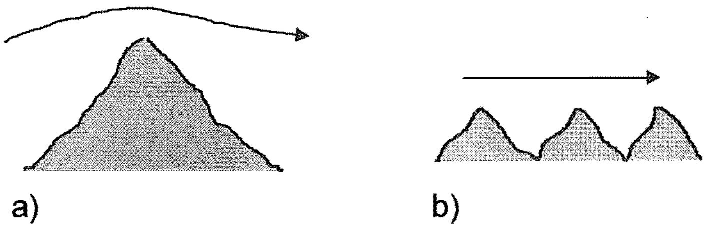


Figure 5.1. Flow over a steep and a number of small hills.

The orographic model used by WAsP is a linear model which is limited to neutrally stable wind flows over low, smooth hills with attached flows. When WAsP generates its Atlas file for a region, it relates wind speed at an actual site to the Atlas value. The accurate speed up correction for terrain effects has an accompanying percentage error E_1 and E_2 (1 = reference site, 2 = predicted site). The error will normally have a positive sign in line with the tendency for WAsP to over-predict rugged sites relative to flat sites [38]. This tendency also applies for the Analysis and Application procedures as the Atlas File represents an imaginary reference site which is flat and featureless. Bowen et al [38] reports that the overall prediction error between predicted and measured wind speed values of a site is determined by the difference in the two individual WAsP procedure errors, (E_2-E_1). The sign of the overall prediction error may be positive or negative depending on the relative magnitude of the two individual procedure errors. A positive sign signifies the over-prediction and a negative sign means under-prediction. The relative sizes of the two procedure errors are considered to be roughly proportional to the individual site ruggedness.

5.3 RUGGEDNESS INDEX PROGRAM

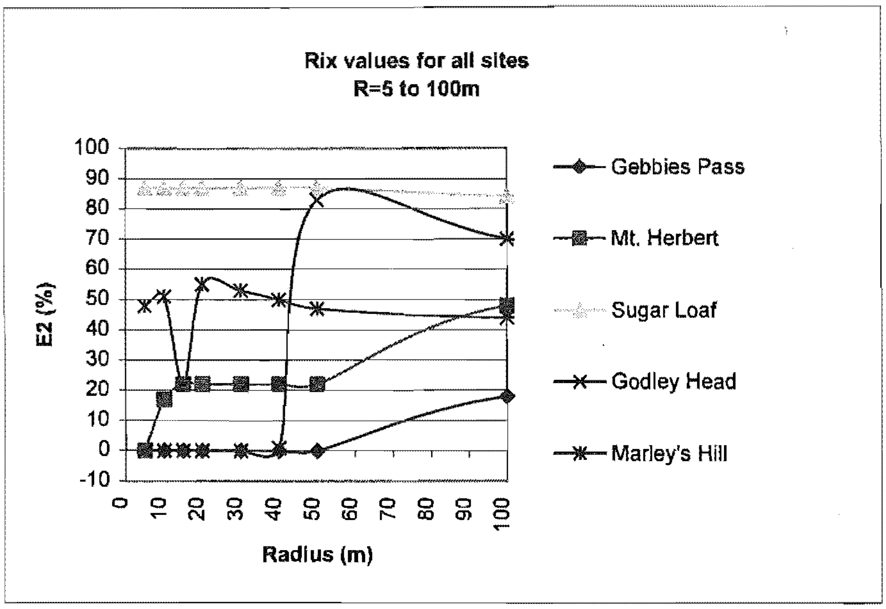
To apply the above technique to a WAsP analysis (e.g. sites on the Port Hills), a practical site indicator is needed to quantify the extent to which the ruggedness of terrain violates the limits implied by the WAsP orographic model. Risϕ National Laboratory of Denmark has developed a computer program called The Ruggedness Index Program (RIX) which calculates the ruggedness values at each site for different hill radii.

The program reads a WAsP Map file and for a given critical slope and radius it then calculates a RIX value for that site. This value represents the percentage of the terrain within radius R which is steeper than the nominated critical slope.

The RIX value for a site is calculated for each 72 radii originating at the site, by dividing each radius into line segments defined by the crossing of the radius with the contour lines. The sum of the line segments representing slopes greater than a critical slope, divided by the total sum of the segments (i.e. the radius) is then the RIX value of the radius in question. The overall RIX value for the site is then simply the mean of the sector-wise RIX values.

5.4 APPLICATION OF RIX PROGRAM TO SITES ON THE PORT HILLS

The RIX program is applied to the sites on the Port Hills to obtain RIX values for different radii from the site summits. The critical slope value is set at 0.3. Results are shown in Table A1.3 in Appendix A1 and plotted in Figure 5.2.



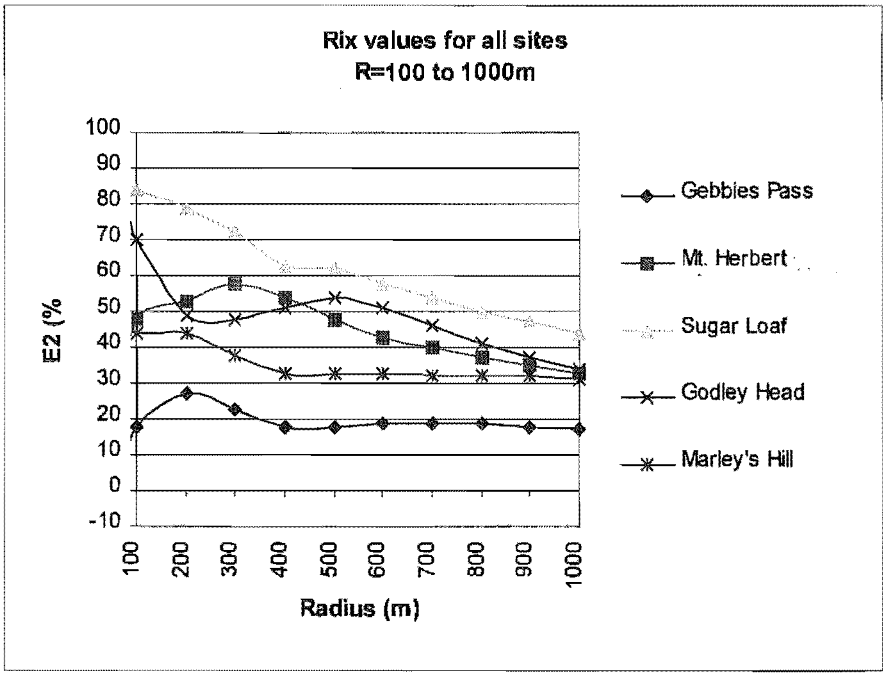


Figure 5.2. Variation of terrain ruggedness values for sites on the Port Hills at different radii shown in two graphs.

The most rugged site, as determined from map contour data, is Sugar Loaf. Its ruggedness drops outside the 50m radius. Marley's Hill (the adjacent site) is less rugged since its top is smoother. The ruggedness curve for the Marley's Hill experiences a sudden drop at R=15m. This is most probably due to the height contour data inefficiencies in the map file (the curve should be smooth). The ruggedness starts to drop at R=20m.

Gebbies Pass, as was expected, demonstrates its good candidacy for wind turbine site developments. The slope gradient is never greater than 0.3 for all sectors around the site until R=50m. Herbert Peak follows the same pattern as Gebbies Pass with steeper slopes for lower heights.

The RIX curve for Godley Head site starts to follow the same pattern as Gebbies Pass. However, the rapid increase in RIX values between R=40 and R=200m is suspect. It was known that the terrain map did not contain adequate height data for this site and the irregularity of the curve is not entirely surprisingly. These curves, suggest that a radius of less than 100m should be considered for any analysis.

5.4.1 WAsP ERRORS AND THE RIX PROGRAM

Tables A1.4 to A1.11 show WAsP predictions of the mean wind speeds for the Port Hills sites and the prediction errors (values inside brackets) compared with field data. For each site, differential RIX values (E_2-E_1) for R=20, 50, and 100m are also tabulated below. The reference wind data is from Christchurch Airport, June 1981 to November 1981 including calms.

Table 5.1. WAsP errors Vs RIX values for the Port Hills Site.

	WAsP (New) mean wind speed (m/s)	**(E_2-E_1) (%) [R=20m]**	**(E_2-E_1) (%) [R=50m]**	**(E_2-E_1) (%) [R=100m]**
Christchurch Airport	4.4 (4%)	0%	0%	0%
Lincoln College	4.0 (-9%)	0%	0%	0%
Gebbies Pass	7.1 (-10%)	0%	0%	18%
Mount Herbert	9.1 (0%)	22%	22%	48%
Sugar Loaf (24m)	9.1 (52%)	87%	87%	84%
Godley Head	8.3 (26%)	0%	83%	70%
Marley's Hill	8.2 (15%)	55%	47%	44%

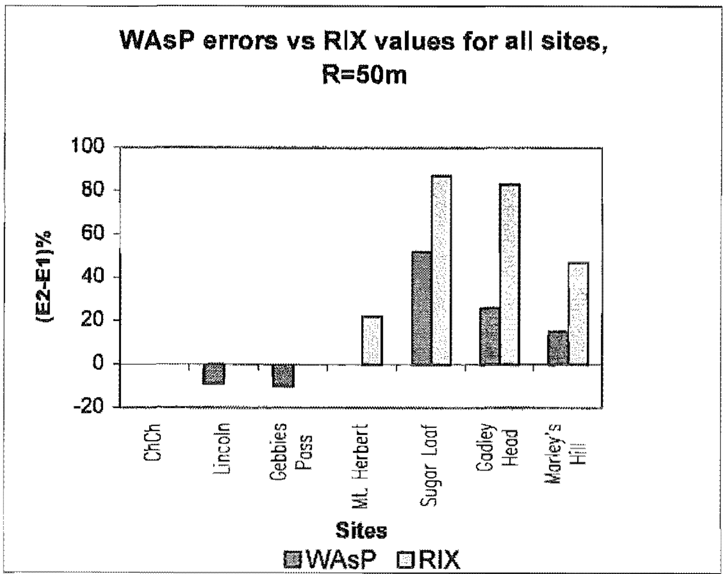


Figure 5.3. Comparison of WAsP errors with RIX values for all sites.

It is expected that for less rugged sites such as Gebbies Pass and Herbert Peak, WAsP mis-predictions would be close to the differential RIX value (E_2-E_1). None of the sites satisfy this expectation (except for the sign) and Gebbies Pass should be the closest. For R=50m, (E_2-E_1) of Gebbies Pass is zero compare with the WAsP under-estimation of 10%. Results for Herbert Peak are less satisfactory. The WAsP estimation is right on the mark whereas the terrain ruggedness error is 20%. For Sugar Loaf, it is promising to see that WAsP errors and RIX calculations are not too far away; also both error values have the same sign, i.e. over-estimation. Overall, RIX values and WAsP errors agree in sign.

Obviously, it is important to decide what radius the RIX value needs to be calculated at for each site. From the results in Table 5.1, R=50 is considered for this investigation which gives a good representation of flow disturbances at the Port Hills sites site.

5.4.2 Site cross-prediction

The above exercise did not really deliver a conclusive and quantitative justification of RIX values. An alternative approach relating the WAsP predictions and terrain ruggedness values is to use cross-predictions between a number of adjacent sites. This is to use wind information at each site on the Port Hills to predict mean wind speeds at other sites and, hence, compare the results with the RIX calculations.

5.4.2.1 Gebbies Pass

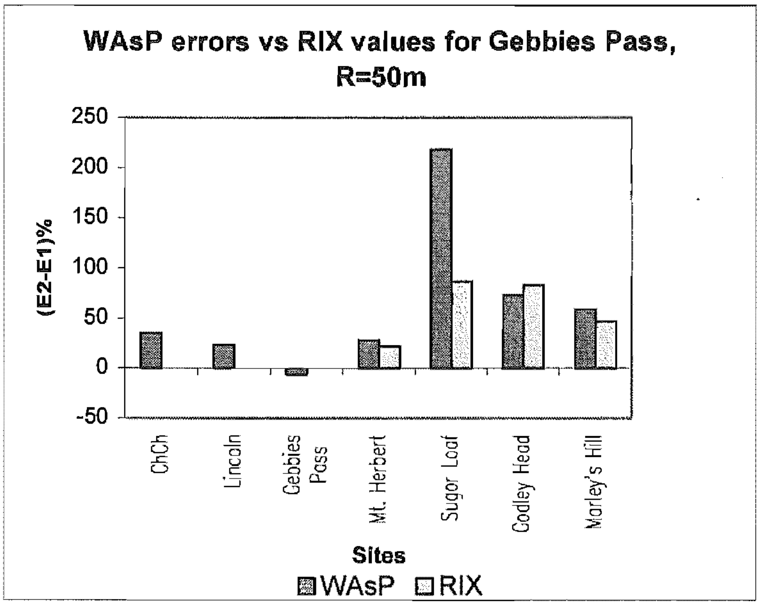


Figure 5.4. Comparison of WAsP errors of WAsP errors with RIX values; Gebbies Pass is the reference site.

It is well accepted from the field observations and confirmed by the RIX program results that wind flowing through the Gebbies Pass is mostly attached. Now, the WAsP program should underestimate wind speeds at sites less rugged than Gebbies Pass (like Christchurch Airport and Lincoln College) and overestimate for sites that are more rugged (such as Herbert Peak, Marley's Hill, Sugar Loaf, and Godley Head). However, it surprisingly overestimates wind speeds at Christchurch Airport and Lincoln, as it does for all the other sites. See Figure 5.4.

The agreement between E_2-E_1 values and WAsP errors for Marley's Hill, Herbert Peak and Godley Head are quite good, both magnitude and sign. But, WAsP over-prediction at Sugar Loaf is an order of magnitude greater than RIX values suggest. In general, RIX calculations follow the same trend and sign as WAsP errors. Comparison is best at R=50m.

5.4.2.2 Herbert Peak

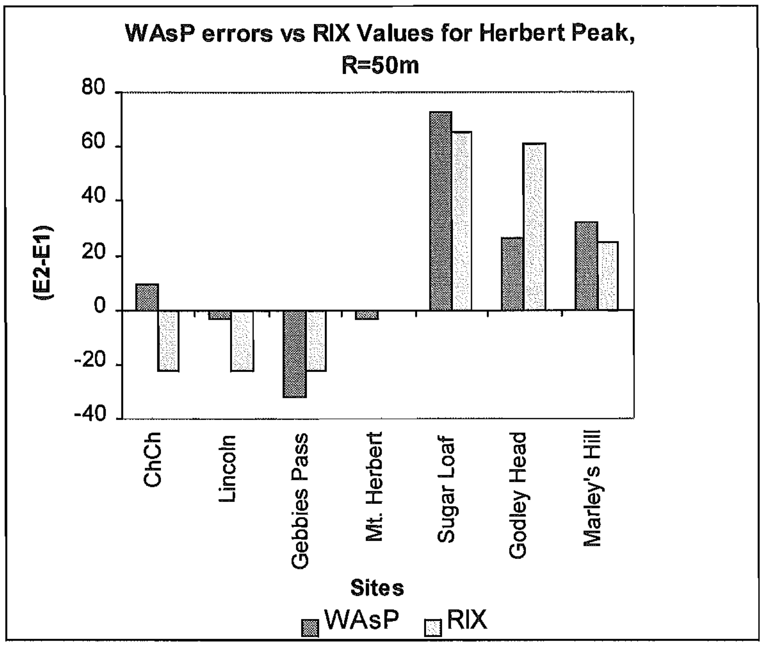


Figure 5.5. Comparison of WAsP errors with RIX values; Herbert Peak is the reference site.

Results in Figure 5.5 demonstrate the expected pattern of under-estimation for the sites less rugged than the reference site (Herbert Peak) and over-estimation for sites with more ruggedness. However, Christchurch Airport behaves otherwise. The comparison between E_2-E_1 and WAsP errors is good for Sugar Loaf this time with error values differing by 8%. Marley's Hill, Sugar Loaf and Godley Head also compare well (with Sugar Loaf and Marley's Hill being the closest). One might suggest that this is due to the fact that both these sites are the next highest sites to Herbert Peak in the Port Hills terrain, which they are all subjected to a high-level wind regime which does not occur at the Christchurch airport (see chapter 4). It is interesting to note that both RIX and WAsP produce negative errors at Gebbies Pass.

5.4.2.3 Marley's Hill

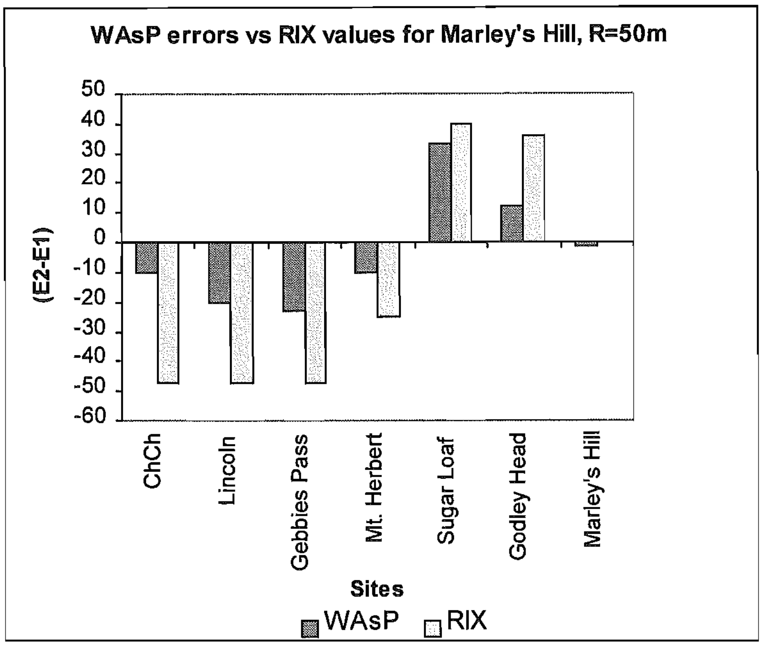


Figure 5.6. Comparison of WAsP errors with RIX values; Marley's Hill is the reference site.

This analysis also produces a similar behaviour in the results. The WAsP under-predicts wind speeds at all sites except Sugar Loaf and Godley Head. Even though the E_2-E_1 signs agree with WAsP errors, its under-prediction percentages cannot really be explained by the RIX program. WAsP overestimation at Sugar Loaf (33%) is closely matched by the E_2-E_1 value (40% at R=50m). See Figure 5.6.

5.4.2.4 Godley Head

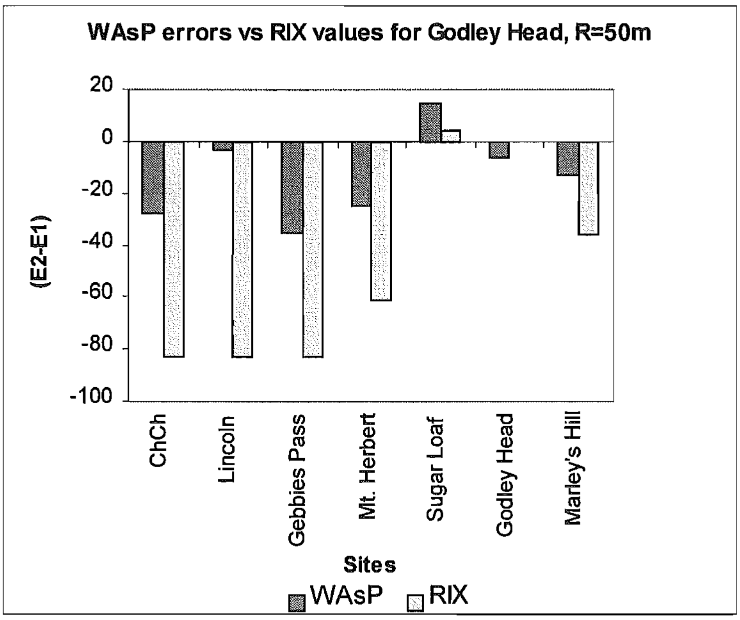


Figure 5.7. Comparison of WAsP errors with RIX values; Godley Head is the reference site.

Although this site lacks adequate height data in the main map file, it produces the same pattern of results. The WAsP and RIX Programs under-predict wind speeds at all sites except Sugar Loaf. The agreement between (E_2-E_1) values and WAsP errors are still poor except for Sugar Loaf. This agrees with the fact that Sugar Loaf is the most rugged site in the Port Hills region.

5.5 GENERAL DISCUSSION

The RIX program confirms the previous hypothesis that WAsP invariably overestimates the mean wind speed for a site which is more rugged than the reference site and vice versa. Using Christchurch Airport as the reference site, WAsP prediction errors agree poorly with the (E_2-E_1) values for different radii of considered terrain. R=50m seems to be an appropriate radius for the Port Hills sites when calculating the RIX values.

In the site cross-prediction analysis, the magnitude and sign of (E_2-E_1) values and WAsP errors compare better, and are quite close for some sites. This agreement is stronger if the reference and predicted sites are exposed to the same wind regime. For example, when Herbert Peak is used as the reference site, the prediction errors are closely predicted by the RIX program for the other high summits of Sugar Loaf and Marley's Hill. Similar results are observed when Marley's Hill and Gebbies Pass are taken as the reference sites. The investigation by Bowen et al [38] of WAsP errors in predicting wind speeds over a hilly region in northern Portugal draws a similar conclusion. They report that to minimise WAsP prediction errors, a high level of cross-correlation in wind speeds between reference and predicted sites is essential. This requires more investigation since the necessary level of correlation still remains ill-defined. For the terrain investigated here, the RIX program calculation of (E_2-E_1) for Sugar Loaf (the most rugged site on the Port Hills) is the most comparable with WAsP errors in the cross-prediction exercise.

The accuracy of WAsP analysis is highly dependent to the terrain map data accuracy. The initial Port Hills map had to be seriously trimmed and truncated so it could include all the interested sites and be loaded into orography model (less than 16,000 data points). This truncation reduces the map accuracy and could have caused some errors in RIX calculations and could possibly explain some of the above unexpected results. To further investigate into this, one could load map of individual sites into the WAsP program without the presence of nearby sites (this approach is also used by Risϕ).

5.6 CONCLUSIONS

As WAsP is increasingly being used for wind energy assessments throughout the world, the RIX program is certainly a valuable tool in calculating the steepness of terrain to indicate the likelihood of flow separation near a site. However, when it is used to determine the degree of WAsP prediction errors, one should be cautious of the results. The outcome is especially sensitive to the radius at which the ruggedness values are calculated. A general knowledge of the area under study is therefore essential. Although the program is relatively easy to use, it is a bit time consuming as for each radius a separate analysis must be performed. Results of the RIX program are also highly dependent on the accuracy of height contours in the map file.

The sign and magnitude of the prediction error due to topography is proportional to the difference in ruggedness between the predicted and reference site. It follows that WAsP is accurate when it is used in rugged terrain as long as $E_1 \approx E_2$. For example, when it is used to compare sites along the same ridge line (of a wind farm say).

The RIX program reads a WAsP Map file and calculates the percentage of the terrain around each site that is steeper than the critical slope (0.3) for the initiation of flow separation. Hence, an indicator to terrain complexity and violation of WAsP performance envelope. The RIX program produces satisfactory results for the Port Hills; in particular for more rugged sites where WAsP mis-predictions are maximum, e.g. Sugar Loaf (the most rugged site on the Port Hills).

The RIX program can also be used to determine the degree of ruggedness around a site for different sectors. In this way, a wind engineer is able to use this quantified ruggedness for a prevailing wind direction to adjust WAsP wind energy predictions.

CONCLUSIONS AND RECOMMENDATIONS

WAsP is a PC based program which was developed for the purpose of wind climate estimation with special regard to wind energy applications. It has fast processing time and is relatively easy to use. WAsP is now increasingly used worldwide in wind turbine site assessments.

The exercise of applying WAsP to Askervein Hill provided a good opportunity to gain experience with the software and to evaluate its capabilities. WAsP prediction of wind speed-ups due to local terrain on the upwind and over the summit side of the hill compare very well with the field data. It clearly picks up both the upwind partial stagnation and the acceleration of the wind over the ridge top. However, it is unable to reliably predict wind speeds in the lee side of the hill where the flow is highly turbulent and separated - the 'wake' region. This inadequacy is more pronounced for 235° direction where wind direction is perpendicular to the major axis of the hill. For the 180° direction, the model predictions fall just within the range of observed data. WAsP also predicts wind speeds adequately for the wind directions where the hill is representing a fully 3-dimensional topographical feature, e.g. 180° direction along the AA and A lines.

WAsP predictions of sites on the Port Hills clearly exhibit WAsP limitations. Its reliability is highly dependent to the accuracy of map data and the raggedness at a site. If a flat and featureless site is used as the reference site, WAsP tends to always over-predict wind speeds at sites with slope greater than 0.3. If the reference site is more rugged than the predicted sites, WAsP tends to under-predict wind speeds.

The WAsP accuracy also depends on to the level of atmospheric correlation between the reference and predicted sites. It is essential that both reference and predicted sites are in the same wind regimes otherwise WAsP predictions can be erroneous.

In the Port Hills analysis, WAsP predictions were best at Herbert Peak and Gebbies Pass when Christchurch Airport was the reference site. Over-prediction at Marley's Hill and Sugar Loaf is partly related to unattached flows (caused by steep slopes) and different atmospheric conditions. A poor prediction at Godley Head is thought to be due to inadequacy of data in the map file. The other influential factor in WAsP mis-predictions is thermal effects, which is totally ignored by WAsP.

In the adequate use of WAsP, it is important to verify the results by using simultaneous measurements from several reference stations - the cross-prediction method. Although this method did not deliver conclusive results, it highlights the importance of cross-correlation factor. In this exercise, Gebbies Pass, in particular, produced unrealistic results both as a predictor and predicted site. It seems that estimation errors get larger with the elevation differential between the predictor and predicted sites. This method can be very useful in gaining confidence in WAsP predictions. Also, it permits to choose the best values of physical parameters in the Parameter File (*WAsP.PAR*), which can exert great influence on the results. For the Port Hills study, P_{34}=0 (true upwind direction in BZ model) produced best predictions.

The RIX program is certainly a valuable tool in calculating the steepness of terrain to indicate the likelihood of flow separation near a site. However, when it is used to determine the degree of WAsP prediction errors, one should be cautious of the results. The outcome is especially sensitive to the radius at which the ruggedness values are calculated. A general knowledge of the area under study is therefore essential. Although the program is relatively easy to use, it is a bit time consuming as for each radius a separate analysis must be performed. One improvement to the program would be to make it to calculate RIX values for several radii, pre selected by the user, at each execution. Results of the RIX program are also highly dependent on the accuracy of height contours in the map file. The sign and magnitude of the prediction error due to topography is proportional to the difference in ruggedness between the predicted and reference site. It follows that WAsP is accurate when it is used in rugged terrain as long as $E_1 \approx E_2$. For example, when it is used to compare sites along the same ridge line (of a wind farm say).

Although the RIX program is useful in quantifying the WAsP errors, but in the end nothing can replace experience and sound judgment. It is necessary to judge carefully the results and they should never be considered final before all the steps that have let to them have been examined and critically evaluated. In addition to the RIX program, it is recommended to use WAsP in conjunction with a suitable software package that can take effects such as thermal stability and thermal inversions into account.

Finally, this research is trusted to have positive contributions to the wind energy applications. The risk aspects of wind power due to poor wind energy predictions have contributed to the high cost of wind power at present time. The research carried out through this study can be applied in wind turbine site assessments to reduce this risk whenever the WAsP program is used. This would enable investors and lenders not to take a worst-case approach (as it is currently practiced) which requires high returns or interest rates.

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APPENDIX A1

TABLES OF RESULTS

Table A1.1. Speed-up values produced by WAsP for each site on the hill.

Site location	Height (a.s.l) (m)	SPEED-UP (%)						
		135°	180°	210°	240°	270°	300°	330°
BSE10	120	8.9	41.3	82.7	66.5	27.3	10.0	13.4
BSE20	119	9.9	41.5	79.2	62.7	26.6	11.1	14.7
BSE30	116	12.9	35.6	67.1	60.8	29.5	13.4	14.9
BSE40	114	16.4	31.9	59.1	61.2	34.1	17.0	16.5
BSE50	112	17.7	31.1	56.2	62.0	37.1	19.5	18.1
BSE60	106	18.5	40.8	61.7	50.0	28.0	19.4	22.5
BSE70	94	9.3	32.4	52.7	39.4	18.0	10.4	13.8
BSE80	82	4.7	24.0	43.7	34.6	14.2	5.5	7.8
BSE90	71	1.1	18.5	37.9	31.0	11.0	1.7	3.5
BSE100	57	-8.4	5.0	26.3	25.5	4.1	-8.3	-8.1
BSE110	48	-8.3	1.7	19.9	23.4	5.3	-7.2	-8.1
BNW10	122	24.7	52.8	81.8	67.2	37.9	25.9	29.4
BNW20	114	33.9	57.7	72.2	56.8	39.2	35.1	39.7
BNW30	90	19.5	36.5	44.3	33.4	22.1	19.8	24.0
BNW40	64	1.6	15.9	25.6	16.9	5.5	2.3	4.9
BNW50	44	-14.4	-2.5	19.9	24.2	1.7	-13.1	-14.1
ANE10	110	16.1	35.2	57.7	50.8	27.8	16.6	18.4
ANE20	87	17.9	20.8	27.2	30.5	25.0	19.2	18.2
ANE30	9	3.9	-8.5	-19.0	-20.5	-14.6	-1.4	4.2
ANE40	42	14.4	-9.2	-21.3	-21.8	-11.3	7.7	9.8
ANE50	27	6.5	-17.8	-28.0	-27.7	-16.5	1.5	0.2
ANE60	18	2.7	-20.3	-37.5	-40.2	-31.3	-8.7	4.3
ANE70	17	2.3	-16.3	-33.9	-37.2	-29.7	-8.6	6.4
ANE80	22	9.4	-17.5	-31.1	-31.9	-20.6	1.0	4.4
ANE90	29	9.0	-14.2	-24.1	-23.8	-12.9	4.3	3.1
ANE100								
ASW10	106	14.8	40.7	65.0	50.3	25.3	15.9	19.6
ASW20	72	7.6	20.6	14.8	6.1	3.3	5.1	13.2
ASW35	31	1.1	-14.8	-21.7	-21.4	-13.4	-1.6	-2.8
ASW30								
ASW50	10	3.7	-17.7	-31.1	-32.5	-23.4	-4.2	1.8
ASW60	9	3.5	-8.5	-19.8	-21.6	-15.9	-2.1	4.6
ASW70	10	3.8	-8.5	-15.1	-15.9	-11.5	0.2	2.8
ASW80	11	1.9	-2.4	-8.8	-10.2	-7.9	-0.9	3.5
ASW90	11	2.6	-1.9	-7.9	-9.1	-6.6	0.0	3.8
ASW100	9	1.6	-1.8	-7.2	-8.3	-6.4	-0.7	3.0

Site location	Height (a.s.l) (m)	SPEED-UP (%)						
		135°	180°	210°	240°	270°	300°	330°
AANE10	111	11.7	41.2	68.0	49.6	22.5	13.1	17.6
AANE20	88	7.8	35.2	33.8	15.6	4.9	5.2	17.1
AANE30	65	10.3	19.3	7.7	-0.8	-1.3	5.5	17.5
AANE40	42	6.0	-10.5	-24.9	-27.2	-20.0	-2.0	7.5
AANE50	31	5.4	-17.3	-35.8	-39.0	-30.3	-6.9	8.6
AANE60	29	5.7	-15.1	-27.9	-29.0	-20.0	-1.5	3.4
AANE70	28	6.2	-20.6	-30.9	-30.3	-17.8	1.8	-1.1
AANE80	31	6.6	-18.7	-27.2	-25.7	-12.6	5.4	-0.7
AANE90	34	7.5	-20.5	-29.6	-28.0	-13.8	6.2	-0.8
AANE100	39	11.4	-21.9	-34.3	-33.7	-19.3	4.9	2.0
AASW10 mf	101	18.3	27.7	44.8	48.6	32.0	19.6	18.6
AASW10 t	101	17.7	27.9	45.5	48.1	30.9	18.7	17.9
AASW20	77	19.0	17.4	18.2	21.1	23.2	21.0	18.1
AASW30 mf	51	16.7	0.4	-6.1	-5.3	3.6	15.3	12.6
AASW30 t	45	9.5	-7.2	-11.1	-8.9	1.7	12.2	4.5
AASW40	24	5.8	-25.0	-33.9	-31.7	-15.7	6.3	-3.9
AASW50 mf	14	4.1	-27.2	-34.6	-31.4	-13.9	8.1	-6.4
AASW50 t	14	5.2	-27.1	-35.4	-32.5	-15.3	7.7	-5.4
AASW60	11	6.9	-13.8	-26.0	-26.9	-17.7	0.2	4.0
AASW70	12	5.0	-7.4	-17.1	-18.2	-12.3	0.3	4.6
AASW80	13	3.4	-2.3	-8.6	-9.7	6.7	0.6	4.2
AASW90	11	3.5	-4.6	-10.7	-11.3	-7.1	0.9	2.9
AASW100								
HT	124	18.5	51.7	88.0	69.4	34.1	19.9	24.1
HT 10 mf	123	18.2	51.5	88.1	69.3	33.9	19.6	23.8
HT t	124	19.0	51.4	87.0	69.2	34.5	20.4	24.4
HT 50m Tower	124	19.4	51.2	86.3	69.3	34.9	20.7	24.5
HT WM	124	21.6	52.4	85.8	69.4	36.4	22.8	26.6
CP Centre Point	114	16.3	31.5	58.3	61.1	34.4	17.2	16.5
CP UK mf	113	15.9	31.6	58.7	60.3	33.3	16.4	16.0
CP BSE40	114	16.3	31.8	58.9	61.2	34.1	17.0	16.5
CP FRG mf	114	16.2	31.6	58.5	61.3	34.4	17.1	16.5
CP FRG 17m tower	117	15.3	35.3	67.1	64.9	33.2	15.4	15.9

Table A1.2. WAsP prediction of vertical velocity profiles for selected wind directions at hilltop (HT)

	Speed-up (ΔS)				
Height (m)	**180°**	**210°**	**270°**	**240°**	**330°**
0.5	0.85	1.61	0.55	1.18	0.39
1.0	0.83	1.59	0.55	1.19	0.37
2.0	0.79	1.50	0.53	1.14	0.35
3.0	0.75	1.39	0.51	1.07	0.34
4.0	0.71	1.27	0.48	0.99	0.33
5.0	0.66	1.16	0.45	0.91	0.31
6.0	0.62	1.08	0.41	0.85	0.29
7.0	0.59	1.02	0.39	0.80	0.27
8.0	0.56	0.97	0.37	0.76	0.26
9.0	0.54	0.92	0.35	0.72	0.25
10.0	0.52	0.88	0.34	0.69	0.24
12.0	0.48	0.82	0.32	0.65	0.22
14.0	0.45	0.77	0.30	0.61	0.21
15.0	0.44	0.74	0.29	0.60	0.20
16.0	0.43	0.72	0.28	0.58	0.19
18.0	0.41	0.69	0.27	0.55	0.19
20.0	0.39	0.66	0.26	0.53	0.18
25.0	0.36	0.59	0.24	0.48	0.17
30.0	0.33	0.54	0.22	0.44	0.15
35.0	0.31	0.50	0.20	0.41	0.15
40.0	0.29	0.47	0.19	0.35	0.14
45.0	0.28	0.44	0.18	0.36	0.13
50.0	0.26	0.42	0.17	0.34	0.13
55.0	0.25	0.39	0.16	0.32	0.12
60.0	0.24	0.37	0.16	0.30	0.12
65.0	0.23	0.36	0.15	0.29	0.11
70.0	0.22	0.34	0.14	0.28	0.11
75.0	0.21	0.32	0.14	0.26	0.10
80.0	0.20	0.31	0.13	0.25	0.10
85.0	0.20	0.30	0.13	0.24	0.10
90.0	0.19	0.29	0.12	0.23	0.09
95.0	0.18	0.27	0.12	0.22	0.92
100.0	0.18	0.26	0.12	0.21	0.09
130.0	0.15	0.21	0.10	0.17	0.08
150.0	0.13	0.19	0.08	0.15	0.07
180.0	0.11	0.16	0.07	0.12	0.06
200.0	0.10	0.14	0.06	0.11	0.06
500.0	0.09	0.13	0.02	0.02	0.02
1000.0	0.01	0.01	0.00	0.00	0.00

Table A1.3. Ruggedness of terrain for each site at different radii (using RIX Program v1.0)

Radius for site (m)	ChCh Airport	Lincoln College	Gebbies Pass	Mt. Herbert	Sugar Loaf	Godley Head	Marley's Hill
	Ruggedness (%)						
	(E_1)		(E_2)				
5	0	0	0	0	87	0	48
10	0	0	0	17	87	0	51
15	0	0	0	22	87	0	22
20	0	0	0	22	87	0	55
30	0	0	0	22	87	0	53
40	0	0	0	22	87	1	50
50	0	0	0	22	87	83	47
100	0	0	18	48	84	70	44
200	0	0	27	53	79	49	44
300	0	0	23	58	72	48	38
400	0	0	18	54	63	51	33
500	0	0	18	48	62	54	33
600	0	0	19	43	58	51	33
700	0	0	19	40	54	46	32
800	0	0	19	37	50	41	32
900	0	0	18	35	47	37	32
1000	0	0	17	33	44	34	31

Table A1.4. WAsP predictions with Gebbies Pass as the predictor, and predicted sites are in the first column. Values inside brackets are WAsP errors. *(Measured wind data at Gebbies Pass for the six month period (June - Nov 1981) is 7.87 m/s)*

	WAsP predictions mean wind speed (m/s)
Christchurch Airport	5.7 **(35%)**
Lincoln College	5.2 **(23%)**
Gebbies Pass	7.5 **(-6%)**
Mount Herbert	12.6 **(28%)**
Sugar Loaf (24m)	13.1 **(218%)**
Godley Head	11.4 **(73%)**
Marley's Hill	11.3 **(59%)**

Table A1.5. Comparison of WAsP errors with RIX values.

	WAsP (New) mean wind speed (m/s)	**(E_2-E_1) (%) [R=20m]**	**(E_2-E_1) (%) [R=50m]**	**(E_2-E_1) (%) [R=100m]**
Christchurc Airport	5.7 **(35%)**	0%	0%	-18%

	WAsP (New) mean wind speed (m/s)	(E_2-E_1) (%) [R=20m]	(E_2-E_1) (%) [R=50m]	(E_2-E_1) (%) [R=100m]
Lincoln College	5.2 **(23%)**	0%	0%	-18%
Gebbies Pass	7.5 **(-6%)**	0%	0%	0%
Mount Herbert	12.6 **(28%)**	22%	22%	30%
Sugar Loaf (24m)	13.1 **(218%)**	87%	87%	66%
Godley Head	11.4 **(73%)**	0%	83%	52%
Marley's Hill	11.3 **(59%)**	55%	47%	52%

Table A1.6. WAsP predictions with Herbert Peak as the predictor and predicted sites are in the first column. Values inside brackets are WAsP errors (*Measured wind data at Mt. Herbert for the six month period (June - Nov 1981) is 9.12 m/s).*

	WAsP predictions mean wind speed (m/s)
Christchurch Airport	4.6 **(9%)**
Lincoln College	4.1 **(-3%)**
Gebbies Pass	5.4 **(-32%)**
Mount Herbert	8.8 **(-3%)**
Sugar Loaf (24m)	10.4 **(73%)**
Godley Head	8.3 **(26%)**
Marley's Hill	9.4 **(32%)**

Table A1.7. Comparison of WAsP errors with RIX values.

	WAsP (New) mean wind speed (m/s)	(E_2-E_1) (%) [R=20m]	(E_2-E_1) (%) [R=50m]	(E_2-E_1) (%) [R=100m]
Christchurc Airport	4.6 **(9%)**	-22%	-22%	-48%
Lincoln College	4.1 **(-3%)**	-22%	-22%	-48%
Gebbies Pass	5.4 **(-32%)**	-22%	-22%	-30%
Mount Herbert	8.8 **(-3%)**	0%	0%	0%
Sugar Loaf (24m)	10.4 **(73%)**	65%	65%	36%
Godley Head	8.3 **(26%)**	-22%	61%	22%
Marley's Hill	9.4 **(32%)**	33%	25%	-4%

Table A1.8. WAsP predictions with Godley Head as the predictor and predicted sites are in the first column. Values inside brackets are WAsP errors *(Measured wind data at Godley Head for the six month period (June - Nov 1981) is 6.6 m/s).*

	WAsP predictions of mean wind speed (m/s)
Christchurch Airport	3.3 (-28%)
Lincoln College	4.1 (-3%)
Gebbies Pass	5.1 (-35%)
Mount Herbert	6.8 (-25%)
Sugar Loaf (24m)	6.9 (15%)
Godley Head	6.2 (-6%)
Marley's Hill	6.2 (-13%)

Table A1.9. Comparison of WAsP errors with RIX values.

	WAsP (New) mean wind speed (m/s)	(E_2-E_1) (%) [R=20m]	(E_2-E_1) (%) [R=50m]	(E_2-E_1) (%) [R=100m]
Christchurc Airport	3.3 (-28%)	0%	-83%	-70%
Lincoln College	4.1 (-3%)	0%	-83%	-70%
Gebbies Pass	5.1 (-35%)	0%	-83%	-52%
Mount Herbert	6.8 (-25%)	22%	-61%	-22%
Sugar Loaf (24m)	6.9 (15%)	87%	4%	14%
Godley Head	6.2 (-6%)	0%	0%	0%
Marley's Hill	6.2 (-13%)	55%	-36%	-26%

Table A1.10. WAsP predictions with Marley's Hill as the predictor and predicted sites are in the first column. Values inside brackets are WAsP errors *(measured wind data at Marley's Hill for the six month period (June - Nov 1981) is 7.1 m/s).*

	WAsP predictions of mean wind speed (m/s)
Christchurch Airport	3.8 (-10%)
Lincoln College	3.4 (-20%)
Gebbies Pass	6.1 (-23%)
Mount Herbert	8.2 (-10%)
Sugar Loaf (24m)	8.0 (33%)
Godley Head	7.4 (12%)
Marley's Hill	7.0 (-1%)

Table A1.11. Comparison of WAsP errors with RIX values.

	WAsP mean wind speed (m/s)	**(E_2-E_1) (%) [R=20m]**	**(E_2-E_1) (%) [R=50m]**	**(E_2-E_1) (%) [R=100m]**
Christchurc Airport	3.8 (-10%)	-55%	-47%	-44%
Lincoln College	3.4 (-20%)	-47%	-47%	-44%
Gebbies Pass	6.1 (-23%)	-44%	-47%	-26%
Mount Herbert	8.2 (-10%)	-32%	-25%	4%
Sugar Loaf (24m)	8.0 (33%)	32%	40%	40%
Godley Head	7.4 (12%)	-55%	36%	26%
Marley's Hill	7.0 (-1%)	0%	0%	0%

APPENDIX A2

METEOROLOGICAL DATA

A2.1 ASKERVEIN HILL

The mean wind speeds and directions measured during the 1982 and 1983 field experiments (Taylor et al, 1987) at RS are tabulated into a meteorological table and stored in ASCII format as specified by WAsP, see Figure A.1. The contents of a histogram file is:

Line 1 is a character string identifying the contents of the file.
Line 2 gives the latitude and longitude of the station and height above ground level of the anemometer. Conventionally, latitude N and longitude E are considered positive. The longitude is not used in WAsP calculations and could be set at any number.
Line 3 states the number of sectors, a scaling factor for wind speed and an offset for direction.
Line 4 gives the frequencies of the occurrence in per cent of wind in various sectors.
Line 5 and onward contain the climatological table, each line corresponding to one wind speed class. First, the upper limit of the speed class is given and then follow the frequencies of occurrence of this class in the sector.

Askervein Hill Wind Data, 1982-1983
74300 20980 48.0
12 1.0 0.00

	0.0	0.0	0.0	9.1	4.5	9.1	11.4	22.7	9.1	27.3	6.8	0
1.0	0	0	0	0	0	0	0	0	0	0	0	0
2.0	0	0	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	1	0	0	0	0
6.0	0	0	0	3	0	0	1	0	1	0	0	0
7.0	0	0	0	1	0	0	1	1	1	0	0	0
8.0	0	0	0	0	0	0	1	4	0	0	1	0
9.0	0	0	0	0	0	0	1	1	1	4	0	0
10.0	0	0	0	0	0	1	0	2	1	4	1	0
11.0	0	0	0	0	0	1	1	1	0	3	1	0
12.0	0	0	0	0	1	0	0	0	0	1	0	0
13.0	0	0	0	0	1	1	0	0	0	0	0	0
14.0	0	0	0	0	0	0	0	0	0	0	0	0
15.0	0	0	0	0	0	1	0	0	0	0	0	0

Figure A2.1. The Askervein Hill histogram file. Wind velocities are in m/s. (Data obtained from the records at Mechanical Department, Canterbury University)

A2.2 CHRISTCHURCH AIRPORT

Figure A. 2 displays the wind data record for Christchurch Airport from 1960 to 1978. The original table obtained from the MetService contains 166,557 readings of wind speeds and velocities, of which 29,152 are 'calm' winds (winds of less than 2 knots). However, it does not give the direction of 'calm' winds and hence they are not included in the table below. The same is true for the data from Lincoln College.

Christchurch Airport Wind Data, Jan 1960-Dec 1978, calms (<2) not included.

	-43.50	172.63	14.00									
	12	0.514	0									
3.72	8.69	24.17	13.63	1.18	0.74	6.62	14.01	12.10	6.40	4.74	4.0	
2.0	402	675	653	1044	130	126	266	381	483	438	255	246
4.0	969	2257	2562	1437	347	272	887	1488	1640	1451	666	536
6.0	1219	3505	5693	2943	437	283	1474	3141	3184	2439	944	712
8.0	728	2184	6466	3392	248	179	1573	3205	3178	2003	651	561
10.0	510	1224	5404	3342	175	81	1279	2748	2425	1128	552	489
12.0	386	881	4777	2933	111	45	1172	2431	1940	504	535	576
14.0	268	519	3164	1844	72	22	831	1698	1189	247	608	503
16.0	245	325	2201	1277	43	14	705	1511	1038	207	667	515
18.0	151	196	1176	622	23	3	366	963	615	98	459	385
20.0	105	100	645	364	16	0	275	692	396	81	460	344
22.0	42	34	233	109	7	0	108	335	170	52	250	162
24.0	34	21	138	39	4	1	62	268	149	37	197	173
26.0	36	7	56	15	3	0	41	183	103	35	171	132
28.0	14	4	21	4	0	0	20	102	51	17	89	60
30.0	4	0	0	0	0	0	11	44	39	18	59	53
32.0	0	1	5	1	0	0	5	19	20	9	23	20
34.0	0	0	2	0	0	0	5	23	10	2	2	12
36.0	0	0	1	0	1	0	0	9	20	3	8	11

Figure A2.2. Christchurch Airport histogram file, excluding calm periods. Wind velocities are in knots. (Data obtained from the records at Mechanical Department, Canterbury University)

Christchurch Airport Wind Data, Jun-Nov 1981

-43.50		172.63	14.00									
	12		1.00		0.00							
	3.6	6.0	16.9	12.8	2.3	1.8	4.5	12.3	16.8	11.0	6.8	5.1
1.00	380	231	83	107	589	760	308	112	82	130	204	273
2.00	120	138	56	38	39	51	51	39	40	86	119	77
3.00	120	173	114	72	88	63	72	76	108	207	139	59
4.00	152	185	161	145	137	89	77	167	203	246	129	82
5.00	76	100	119	191	39	38	62	106	165	136	58	59
6.00	44	85	140	172	69	0	159	151	157	102	85	100
7.00	38	58	114	111	29	0	97	93	99	54	58	64
8.00	19	23	83	47	10	0	67	72	72	29	64	105
9.00	25	0	61	47	0	0	56	39	26	2	54	45
10.00	13	4	43	43	0	0	0	74	22	4	24	41
11.00	6	4	16	20	0	0	15	37	7	4	27	32
12.00	6	0	8	9	0	0	15	13	7	0	24	36
13.00	0	0	1	0	0	0	5	11	1	0	7	14
14.00	0	0	0	0	0	0	15	4	7	0	7	5
15.00	0	0	0	0	0	0	0	6	4	0	0	5
16.00	0	0	0	0	0	0	0	0	1	0	3	0
17.00	0	0	0	0	0	0	0	0	0	0	0	5

Figure A2.3. Christchurch Airport histogram file compiled from a time-series wind data file. Calm periods are included and wind velocities are in m/s. (Data obtained from NIWA)

A2.3 LINCOLN COLLEGE SITE

Lincoln University Wind Data, May 1975 to April 1978.

-43.65 172.47 10.00

12 0.514 0

	8.72	22.41	17.93	1.55	1.29	5.20	10.72	9.65	7.93	6.53	3.24	6.64
2.0	221	198	185	93	81	96	133	133	139	218	117	154
4.0	437	641	312	99	96	209	260	264	342	382	181	201
6.0	340	637	314	38	46	208	279	226	264	305	87	121
8.0	259	720	389	24	18	260	332	195	181	135	43	90
10.0	155	720	515	15	5	131	352	209	174	85	37	99
12.0	80	565	502	9	3	87	253	204	129	60	33	116
14.0	56	343	402	9	0	54	173	181	85	34	27	106
16.0	39	253	362	11	0	31	150	182	76	19	29	105
18.0	39	149	255	2	0	15	74	114	54	8	19	93
20.0	21	67	118	0	1	2	29	82	29	7	22	64
22.0	25	29	77	0	0	1	20	36	16	6	10	53
24.0	7	8	29	0	0	1	14	23	20	3	8	31
26.0	6	2	5	0	0	0	3	12	11	0	7	23
28.0	2	0	1	0	0	0	1	3	11	0	1	14
30.0	1	0	0	0	0	0	0	2	0	0	4	7
32.0	0	0	0	0	0	0	0	0	1	0	1	4
34.0	0	0	0	0	0	0	0	0	0	0	1	1
36.0	0	0	0	0	0	0	0	0	0	0	0	1

Figure A2.4. Lincoln Site histogram file, excluding calm periods. Wind velocities are in knots. (Data obtained from the Meteorology Department of Lincoln University)

A2.4 Gebbies Pass Site

Wind Data for Gebbies Pass from 6/81 to 11/81. Anemometer Height = 10 m (a.g.l.)

-43.68 172.63 10.0

8 0.5144 0.0

	38.01	13.60	0.2	0.0	11.95	31.03	3.73	1.48
2.0	25	5	1	0	7	45	5	0
4.0	101	30	4	1	15	110	16	2
6.0	99	28	2	0	20	111	15	4
8.0	114	34	0	0	24	128	21	5
10.0	141	49	0	0	34	139	17	8
12.0	164	31	0	0	43	129	21	17
14.0	156	34	0	0	41	90	10	5
16.0	175	44	0	0	44	84	15	6
18.0	159	31	0	0	38	92	10	5
20.0	106	26	0	0	26	61	6	5
22.0	79	20	0	0	26	68	6	2
24.0	47	29	1	0	21	57	2	0
26.0	32	24	0	0	24	24	2	0
28.0	39	17	0	0	32	25	1	0
30.0	23	27	0	0	24	14	2	0
32.0	34	29	0	0	20	21	0	0
34.0	9	32	0	0	13	21	0	0
36.0	7	31	0	0	13	13	0	0
38.0	7	24	0	0	9	7	0	0

Figure A2.5. Gebbies Pass Site histogram file, excluding calm periods. Wind velocities are in knots. (Data obtained from Smyth [36])

A2.5 Mt Herbert Site

Wind Data for Mt Herbert from 6/81 to 11/81. Anemometer Height = 10 m (a.g.l.)

	-43.73		172.67		10.0				
	8	0.5144		-45					
		26.04	4.58	1.16	28.73	7.37	6.54	10.10	15.48
2.0		4	1	1	5	0	5	2	0
4.0		20	9	3	33	14	21	11	12
6.0		34	8	6	37	15	16	11	30
8.0		39	16	4	38	14	9	21	22
10.0		62	11	1	43	15	14	7	19
12.0		38	13	5	45	22	13	11	29
14.0		47	15	6	30	10	16	14	19
16.0		41	11	1	35	21	8	15	20
18.0		57	2	1	54	15	11	17	33
20.0		42	4	0	52	12	10	27	32
22.0		40	4	0	35	14	9	25	27
24.0		25	0	0	42	10	13	16	33
26.0		35	3	0	27	4	5	11	21
28.0		32	7	0	29	8	4	13	17
30.0		22	6	0	33	2	3	10	8
32.0		21	1	0	30	2	0	7	12
34.0		21	0	0	25	0	1	7	16
36.0		6	0	0	16	0	0	3	6
38.0		8	0	0	24	0	0	2	6

Figure A2.6. Herbert Peak Site histogram file, excluding calm periods. Wind velocities are in knots. (Data obtained from Smyth [36])

A2.6 MARLEY'S HILL SITE

Wind Data for Marley's Hill from 6/81 to 11/81. Anemometer Height = 30 m (a.g.l.)

-43.68		172.63		30.0				
8	0.5144		0					
	6.77	9.85	24.4	4.48	16.08	19.13	8.55	10.68
2.0	3	7	8	7	4	2	6	2
4.0	24	37	45	20	23	13	25	17
6.0	30	59	68	34	38	33	31	21
8.0	33	49	97	21	52	50	38	24
10.0	25	59	123	36	92	67	43	28
12.0	43	26	75	16	64	99	31	32
14.0	25	18	62	5	56	78	24	30
16.0	19	13	81	5	60	69	27	36
18.0	10	21	68	5	39	60	33	44
20.0	11	12	68	10	26	39	13	44
22.0	5	13	56	0	23	46	21	45
24.0	10	14	61	1	28	34	14	15
26.0	6	11	34	0	19	27	3	15
28.0	1	9	20	0	31	21	4	12
30.0	2	5	13	0	22	13	3	15
32.0	4	5	11	0	7	20	1	8
34.0	0	1	5	0	3	13	0	3
36.0	0	4	6	0	1	5	0	4
38.0	0	1	5	0	6	4	0	0

Figure A2.7. Marley's Hill Site histogram file, excluding calm periods. Wind velocities are in knots. (Data obtained from Smyth [36])

A2.7 GODLEY HEAD SITE

Wind Data for Godley Head from 6/81 to 11/81. Anemometer Height = 10 m (a.g.l.)

	-55.7	-167.90		10.0				
	8	0.5144		0				
	6.03	12.42	20.48	5.25	12.09	25.28	14.3	4.15
2.0	14	16	15	10	85	18	27	3
4.0	42	41	79	33	101	52	82	18
6.0	33	60	100	29	60	55	69	15
8.0	34	67	133	8	48	68	79	19
10.0	42	90	141	20	36	83	69	14
12.0	12	71	133	20	38	67	51	11
14.0	10	24	97	22	30	94	48	16
16.0	10	29	71	16	19	120	44	14
18.0	10	44	39	13	22	106	39	16
20.0	7	26	20	12	9	56	24	19
22.0	13	31	12	13	7	60	25	5
24.0	6	11	10	8	12	45	10	9
26.0	4	9	7	4	5	47	9	5
28.0	5	2	6	5	7	34	7	0
30.0	2	3	7	5	7	45	3	1
32.0	3	2	2	4	7	29	9	2
34.0	2	2	1	2	7	25	9	3
36.0	2	2	1	0	3	10	3	1
38.0	4	0	0	0	2	12	0	0

Figure A2.8. Godley Head Site histogram file, excluding calm periods. Wind velocities are in knots. (Data obtained from Smyth [36])

APPENDIX A3

BATCH FILES

A3.1 ASKERVEIN HILL

Because of the large number of sites on Askervein Hill, execution of WAsP proved to be a very time consuming job. Therefore, a batch file was prepared to do the task automatically.

In batch mode the input to WAsP comes from an ASCII disk file rather than a keyboard. Figure A3.1 shows the input file which contains commands and input data in exactly the same format and order as it would have been given in interactive mode. Comments inside brackets {} are for information only and not included in the original batch file.

Figure A3.1. The batch file which runs WAsP session for each individual site on Askervein Hill and stores the data in a file. Note: contents of this file was printed in three columns to save paper space.

```
Dat   {opens DATA menu}
tab   {prompts for climatological Table}
c:\askervei\wind\askervei
  16  27    {scape}
            {enter}
-obs        {no Obstacles}
rou         {opens Rroughness menu}
tex         {prompts for Z_0}
Roughness Length = 3 cm.

Oro         {opens Orographic menu}
map         {prompts for Map File}
rel         {reloads digitised map file}
c:\askervei\maps\aski

sit         {gets site coordinates}
  16  27
74300,20980
atl         {opens wind ATLAS menu}
gen         {GENERATES a wind atlas data set}

oro
sit
  16  27
75243,23875

:c:\askervei\dump\aski8.dmp
>           {stores the results screen on C:\...}
>           {stores the status screen on C:\...}
oro
sit
  16  27
75313,23810

>
>
oro
sit
  16  27
75175,23948

>
>
oro
sit
  16  27
75107,24021

>
>
oro
sit
  16  27
75039,24094

>
>
oro
sit
  16  27
75383,23737

>
>
oro
sit
  16  27
75387,23735

>
>
oro
sit
  16  27
75381,23745

>
>
```

oro
sit
16 27
75381,23753

>
>
oro
sit
16 27
75360,23763

>
>
oro
sit
16 27
75746,23540

>
>
oro
sit
16 27
75807,23610

>
>
oro
sit
16 27
75871,23675

>
>
oro
sit
16 27
75938,23745

>
>
oro
sit
16 27
76006,23813

>
>
oro
sit
16 27
76073,23886

>
>
oro
sit
16 27
76146,23954

>
>
oro
sit
16 27
76219,24022

>
>
oro
sit
16 27
76292,24090

>
>
oro
sit
16 27
76365,24158

>
>

oro
sit
16 27
75454,23812

>
>
oro
sit
16 27
75523,23884

>
>
oro
sit
16 27
75661,24017

>
>
oro
sit
16 27
75734,24085

>
>
oro
sit
16 27
75807,24153

>
>

oro
sit
16 27
75880,24221

>
>
oro
sit
16 27
75953,24289

>
>
oro
sit
16 27
76026,24357

>
>

oro
sit
16 27
75319,23667

>
>
oro
sit
16 27
75257,23604

>
>
oro
sit
16 27
75162,23498

>
>
oro
sit
16 27
75050,23378

>
>
oro
sit
16 27
74970,23295

>
>
oro
sit
16 27
74977,23310

>
>
oro
sit
16 27
74904,23242
>
>
oro
sit
16 27
74831,23174

>
>
oro
sit
16 27
74758,23106

>
>
oro
sit
16 27
74685,23038

>
>

oro
sit
16 27
75458,23671

>
>
oro
sit
16 27
75528,23603

>
>
oro
sit
16 27
75606,23535

>
>
oro
sit
16 27
75680,23465

>
>

oro
sit
16 27
75754,23397

>
>
oro
sit
16 27
75833,23324

>
>
oro
sit
16 27
75905,23260

>
>
oro
sit
16 27
75982,23193

>
>
oro
sit
16 27
76046,23130

>
>
oro
sit
16 27
76120,23063

>
>
oro
sit
16 27
76195,22997

>
>
oro
sit
16 27
75675,23465

>
>
oro
sit
16 27
75686,23457

>
>
oro
sit
16 27
75680,23464

>
>
oro
sit
16 27
75676,23466

>
>
oro
sit
16 27
75688,23493

>
>
oro
sit
16 27
75613,23396

>
>
oro
sit
16 27
75623,23388

>
>
oro
sit
16 27
75553,23320

>
>
oro
sit
16 27
75483,23253

>
>
oro
sit
16 27
75493,23224

>
>
oro

```
sit
  16 27
75417,23174

>
>
oro
sit
  16 27
75341,23107

>
>
oro
sit
  16 27
75352,23100

>
>
oro
sit
  16 27
75274,23038
>
>
oro
sit
  16 27
75208,22968

>
>
oro
sit
  16 27
75140,22895

>
>
oro
sit
  16 27
75069,22820

>
>
sto
```

A3.2 PORT HILLS

Figure A3.2. The batch file which runs WAsP session for each individual site on the Port Hills and stores the data in a file. Note: contents of this file was printed in three columns to save paper space.
Wind Data from Christchurch Airport, June to November 1981.

```
dat  {opens DATA menu}
tab  {prompts for climatological table}
c:\porthill\wind\chcharp2.tab {wind data June to
                               Nov 1981}
  16 27

-obs

oro
map
rel
c:\maps\final.map

sit
  16 27
2473610,5747290  {Christchurch Airport}
rou  {opens roughness menu}
edi  {prompts for Z0}
0,360:0.03     Roughness Length = 3 cm.


atl
gen

hei
14

:d:\waspnew\dump\final
>
>

oro
sit
  16 27
2489137,5724197  {Herbert Peak}

hei
10
rou
edi
0,360:0.03


>
>
oro
sit
  16 27
2480539,5732729  {Marley's Hill}
```

```
hei
30
rou
edi
0,360:0.1


>
>
hei
10

>
>
oro
sit
  16  27
2481725,5733769   {Sugar Loaf}

hei
24
rou
edi
0,360:0.03


>
>
hei
122

>
>
oro
sit
  16  27
2493126,5735089   {Gebbies Pass}

hei
10
rou
edi
0,360:0.03


>
>

oro
sit
  16  27
2480264,5724907   {Godley Head}

>
>
oro
map
rel
c:\maps\lincoln2.map

sit
  16  27
2467000 5728800 {Lincoln College}

rou
edi
0,360:0.04


obs {load Obstacle File}
rel
c:\porthill\obstacle\lincoln

hei
10


>
>
sto   {End of session}
```

Figure A3.3. The batch file which runs WAsP session for each individual site on the Port Hills and stores the data in a file. Note: contents of this file was printed in three columns to save paper space.

Wind Data from Lincoln College.

```
dat
tab
c:\porthill\wind\lincoln.tab
  16  27


oro
map
rel
c:\maps\lincoln2.map

sit
  16  27
2467000 5728800

rou
edi
0,360:0.04
```

```
obs
rel
c:\porthill\obstacle\lincoln


atl
gen


hei
10

:d:\waspnew\dump\lincoln

>
>


oro
map
rel
c:\maps\final.map

sit
  16  27
2489137,5724197

-obs

hei
10
rou
edi
0,360:0.03



>
>
oro
sit
  16  27
2480539,5732729

hei
30
rou
edi
0,360:0.1



>
>
hei
10

>
>
oro
sit
  16  27
2481725,5733769

hei
24
rou
edi
0,360:0.03



>
>
hei
122

>
>
oro
sit
  16  27
2493126,5735089

hei
10
rou
edi
0,360:0.03



>
>

oro
sit
  16  27
2473610,5747290

hei
14

rou
edi
0,360:0.02



>
>

oro
sit
  16  27
2480264,5724907

>
>
```

```
oro
map
rel
c:\maps\lincoln2.map

sit
  16 27
2467000 5728800
rel
c:\porthill\obstacle\lincoln

hei
10

rou
edi
0,360:0.04

obs

>
>
sto
```

A3.3 RIX PROGRAM BATCH FILES.

The RIX Program was run with a Batch files for each site individually to calculate the ruggedness at different radii. Figures A3.3a and A3.3b show a sample Batch file prepared for Mount Herbert site. The other batch files are similar; only the site coordinate reference differs.

```
rix c:\maps\phrug 2493126 5735089 -r5.0 -o gh0
rix c:\maps\phrug 2493126 5735089 -r 10.0 -o gh1
rix c:\maps\phrug 2493126 5735089 -r 15.0 -o gh2
rix c:\maps\phrug 2493126 5735089 -r 20.0 -o gh3
rix c:\maps\phrug 2493126 5735089 -r 30.0 -o gh4
rix c:\maps\phrug 2493126 5735089 -r 40.0 -o gh5
rix c:\maps\phrug 2493126 5735089 -r 50.0 -o gh6
rix c:\maps\phrug 2493126 5735089 -r 100.0 -o gh7
rix c:\maps\phrug 2493126 5735089 -r 200.0 -o gh8
rix c:\maps\phrug 2493126 5735089 -r 300.0 -o gh9
rix c:\maps\phrug 2493126 5735089 -r 400.0 -o gh10
rix c:\maps\phrug 2493126 5735089 -r 500.0 -o gh11
rix c:\maps\phrug 2493126 5735089 -r 600.0 -o gh12
rix c:\maps\phrug 2493126 5735089 -r 700.0 -o gh13
rix c:\maps\phrug 2493126 5735089 -r 800.0 -o gh14
rix c:\maps\phrug 2493126 5735089 -r 900.0 -o gh15
rix c:\maps\phrug 2493126 5735089 -r 1000.0 -o gh16
```

Figure A3.4a. The Batch file.

site name	(x, y)	rix	sectors											
user	(2.48918e+006, 5.7	0	0	0	0	0	0	0	0	0	0	0	0	0
user	(2.48918e+006, 5.7	17	0	0	0	0	0	0	0	0	23	100	83	0
user	(2.48918e+006, 5.7	22	0	0	0	0	0	0	0	0	100	100	71	0
user	(2.48918e+006, 5.7	22	0	0	0	0	0	0	0	0	100	100	69	0
user	(2.48918e+006, 5.7	22	0	0	0	0	0	0	0	0	100	100	68	0
user	(2.48918e+006, 5.7	22	0	0	0	0	0	0	0	0	100	100	67	0
user	(2.48918e+006, 5.7	22	0	0	0	0	0	0	0	0	100	100	67	3
user	(2.49313e+006, 5.7	49	12	15	16	17	19	36	60	100	100	86	94	33
user	(2.48918e+006, 5.7	53	14	100	100	81	24	3	0	48	100	100	66	5
user	(2.48918e+006, 5.7	58	15	100	100	90	61	16	0	61	90	100	65	3
user	(2.48918e+006, 5.7	54	15	80	83	88	74	21	0	59	79	100	53	2
user	(2.48918e+006, 5.7	48	14	61	63	69	80	24	0	47	73	100	42	1
user	(2.48918e+006, 5.7	43	13	49	51	55	84	29	0	39	64	98	35	1
user	(2.48918e+006, 5.7	40	16	41	43	46	86	35	0	33	57	93	30	1
user	(2.48918e+006, 5.7	37	18	35	37	39	87	39	0	29	51	85	26	1
user	(2.48918e+006, 5.7	35	20	31	32	34	86	43	0	25	47	78	23	1
user	(2.48918e+006, 5.7	33	19	28	29	31	85	48	0	23	46	71	22	0

Figure A3.4b. Results of RIX calculations. Each line correspondes to the line in above figure. RIX values are given both overall and individually for each sector.

APPENDIX A4

WAsP PREDICTIONS

The WAsP program summarises its prediction of wind climate for each site into two tables as displayed in Figures 2.3 and 2.4. These are stored onto a diskette (attached with the body of this thesis) in their original WAsP format.